SKN 3022
PROCESS INSTRUMENTATION
CHAPTER V

SIGNAL MODIFIER

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SIGNAL MODIFIER

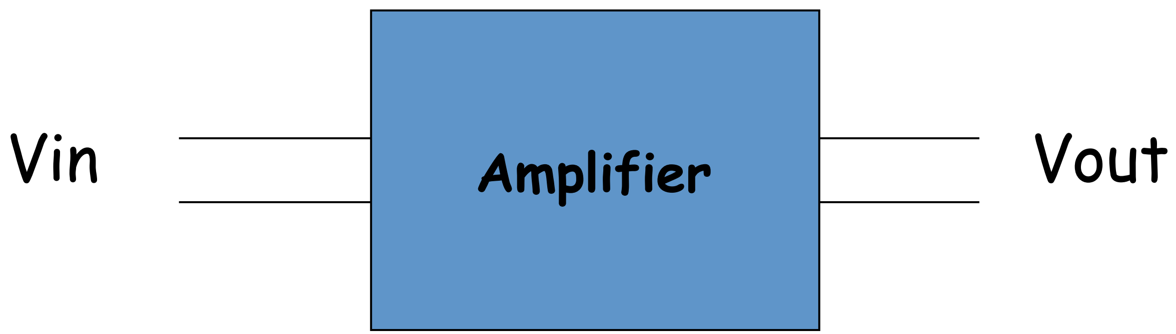
- The output signal from a transducer usually need to be modified through signal modifier (conditioner).
- Several types of signal modifier commonly used in the industry are:
  - Amplifier (Op-Amp)
  - Analog to Digital Converter (ADC)
  - Digital to Analog Converter (DAC)
  - Frequency Filter
  - Noise Filter

AMPLIFIER

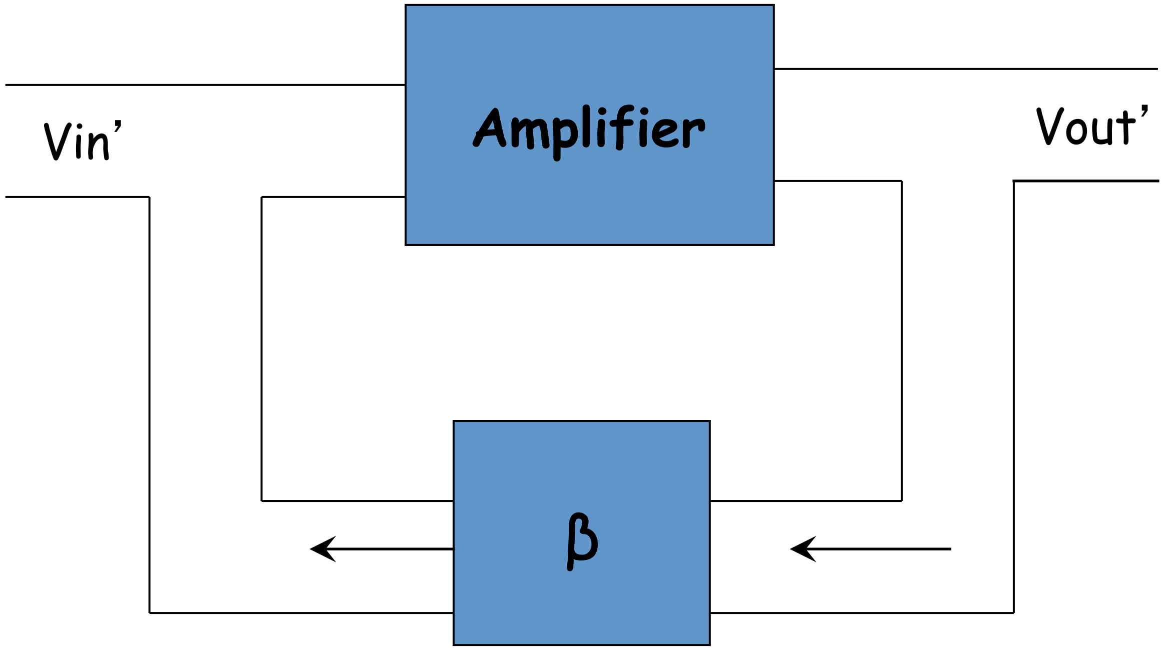
- **Device that amplifies the signal's amplitude from the transducer so that it can be displayed or recorded.**
- **For amplifier without any feed, voltage multiplication (Av) is obtained through the output voltage (V_{out}) to input voltage (V_{in}) ratio.**

- **Av = V_{out}/ V_{in}.**
- **Output voltage is amplified through power factor (A) and input voltage.**
- **Av is known as "open-loop gain" if there is no feedback.**
- **If the amplifier is being fed, Av is known as closed-loop gain where Av' = V_{out}/V_{in}'.**

Open-Loop Condition



Closed-Loop Condition:



Feedback Loop

Feedback Amplifier

- Part of the amplifier output are feedback into the input circuit.
- Consist of two parts, which are: amplifier circuit and feedback circuit.
- There are two types of feedback amplifier: positive and negative amplifier

i. Positive Feedback Amplifier

- Feedback voltage/current will increase the input voltage and in-phase.
- A lot of distortion.
- Rarely use in amplifier.
- Use in “oscillator” circuit.

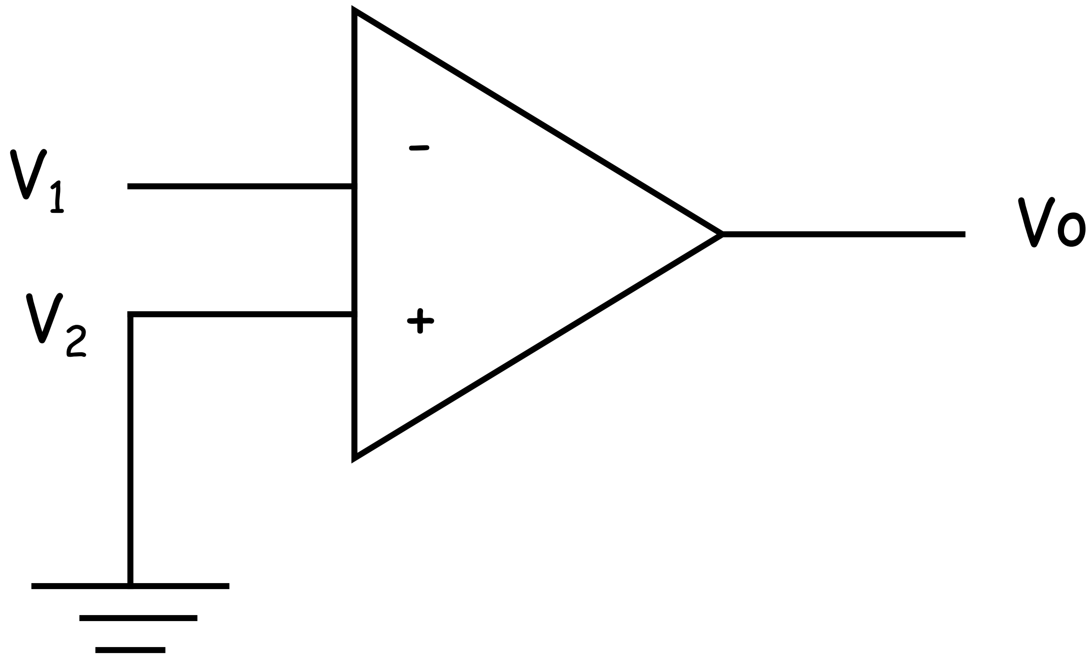
ii. Negative Feedback Amplifier

- Feedback voltage/current will reduce the amplifier input and it is not in phase (180°C out-of-phase).
- Often use in amplifier system.
- Among the advantages:
  - more linear operation
  - more stabilize power factor
  - less amplitude distortion
  - less phase distortion
  - input and output can be modify as desirable.

OPERATIONAL AMPLIFIER (OP-AMP)

- Consists of negative feedback amplifier.
- Designated for solving mathematical operations (i.e +,-,÷,*).
- Eventhough OP-AMP is a complete system, but the outside component can be connected to the amplifier terminal to change it's real characteristics and functions.

- Suitable for all apllication and often being use in industries.
- Each OP-AMP has 5 terminals:
  1. Inverting terminal (terminal V_1).
  2. Non-inverting terminal (terminal V_2).
  3. Output terminal (Vo).
  4. Positive bias supply terminal.
  5. Negative bias supply terminal.



V1
V2
-
+
Vo

IDEAL OP-AMP

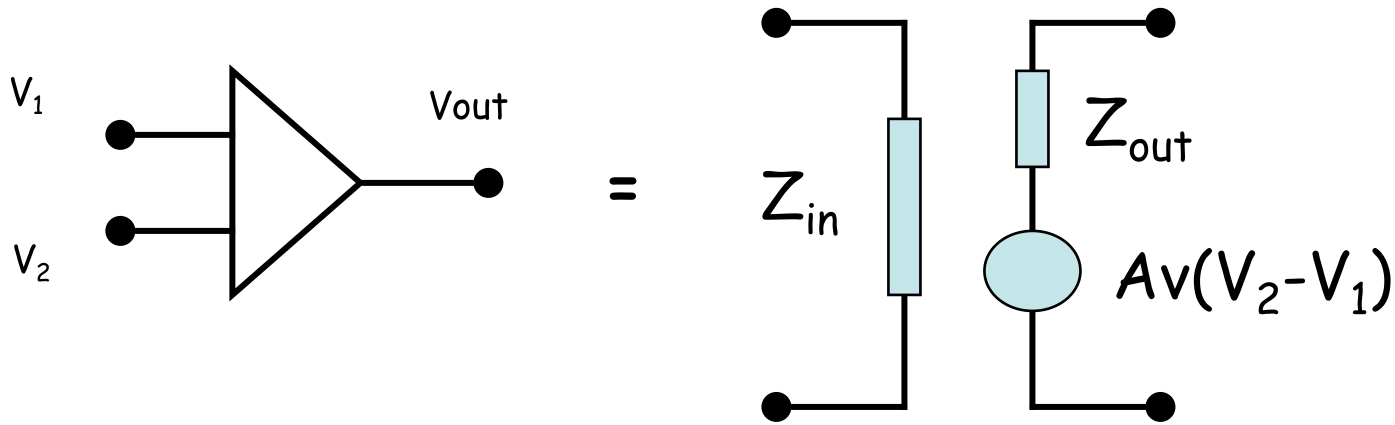
Ideal characteristics of OP-AMP are:

1. **Open-loop gain (Av) is infinity.**
2. **Resistor's input value, Ri (which is measured between inverting and non-inverting terminal) is infinity, this shows that OP-AMP is a voltage-controlled device.**

3. **Output resistance value, Ro (observed from an output terminal) is zero, which means that Vo is independent of resistor loads which is connectted to the output.**
4. **Bandwidth is infinity i.e. has a linear frequency.**
5. **Eventhough these characteristics will not be achived in practical, it is important as a reference in looking for the true accuracy of OP-AMP.**

EXAMPLE OF OP-AMP APPLICATION

i. Scaler/linear amplifier
ii. Adder
iii. Subtractor
iv. Integrator
v. Differentiator etc.

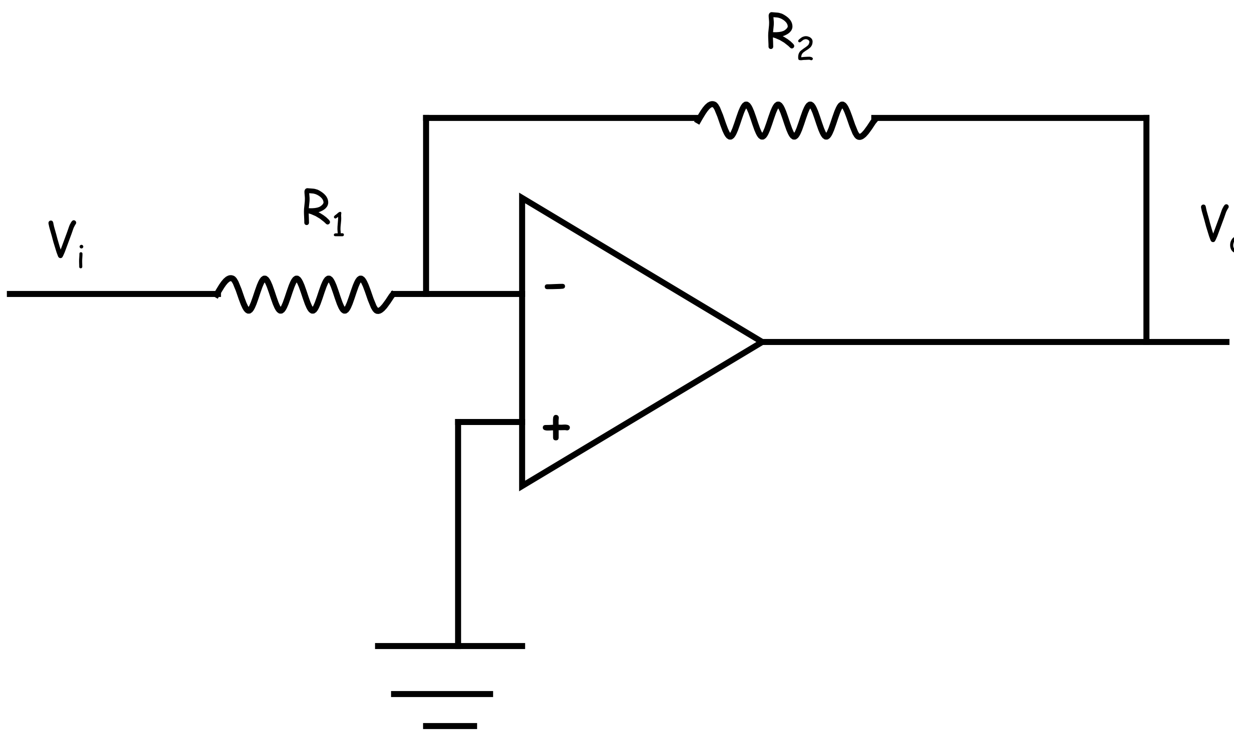


Parameter	Ideal OP-AMP	Typical OP-AMP
DC Open Loop gain	ω	10^5
Input impedance	ω	2 M Ω
Output impedance	0	75 Ω
Common Mode Rejection Ratio (CMRR)	ω	3×10^4 ‹‹‹

The above table shows the characteristic of ideal OP-AMP and typical OP-AMP.

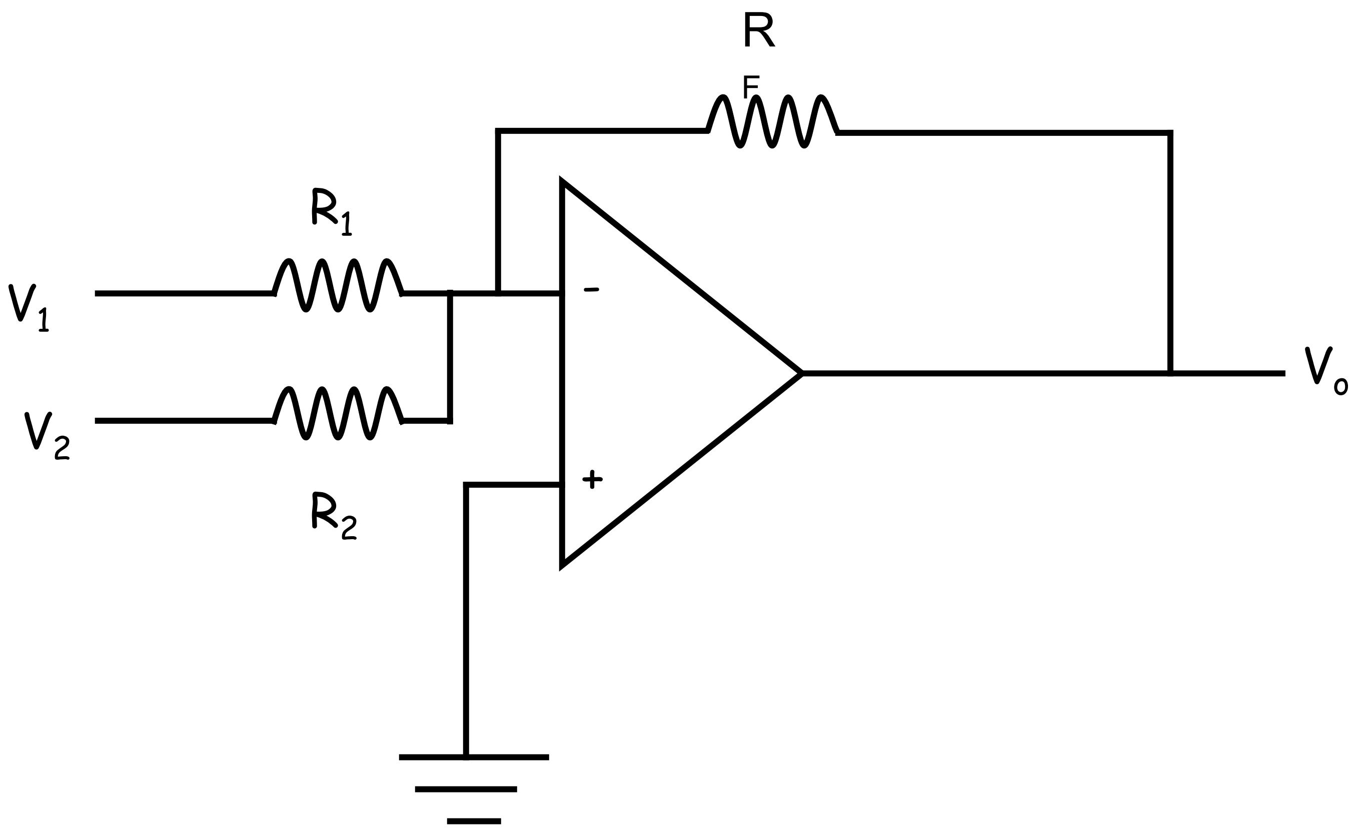
$$CMRR = \frac{A_{OL} \text{ (open-loop gain)}}{A_{CM} \text{ (common-mode gain)}}$$

1. Linear Amplifier



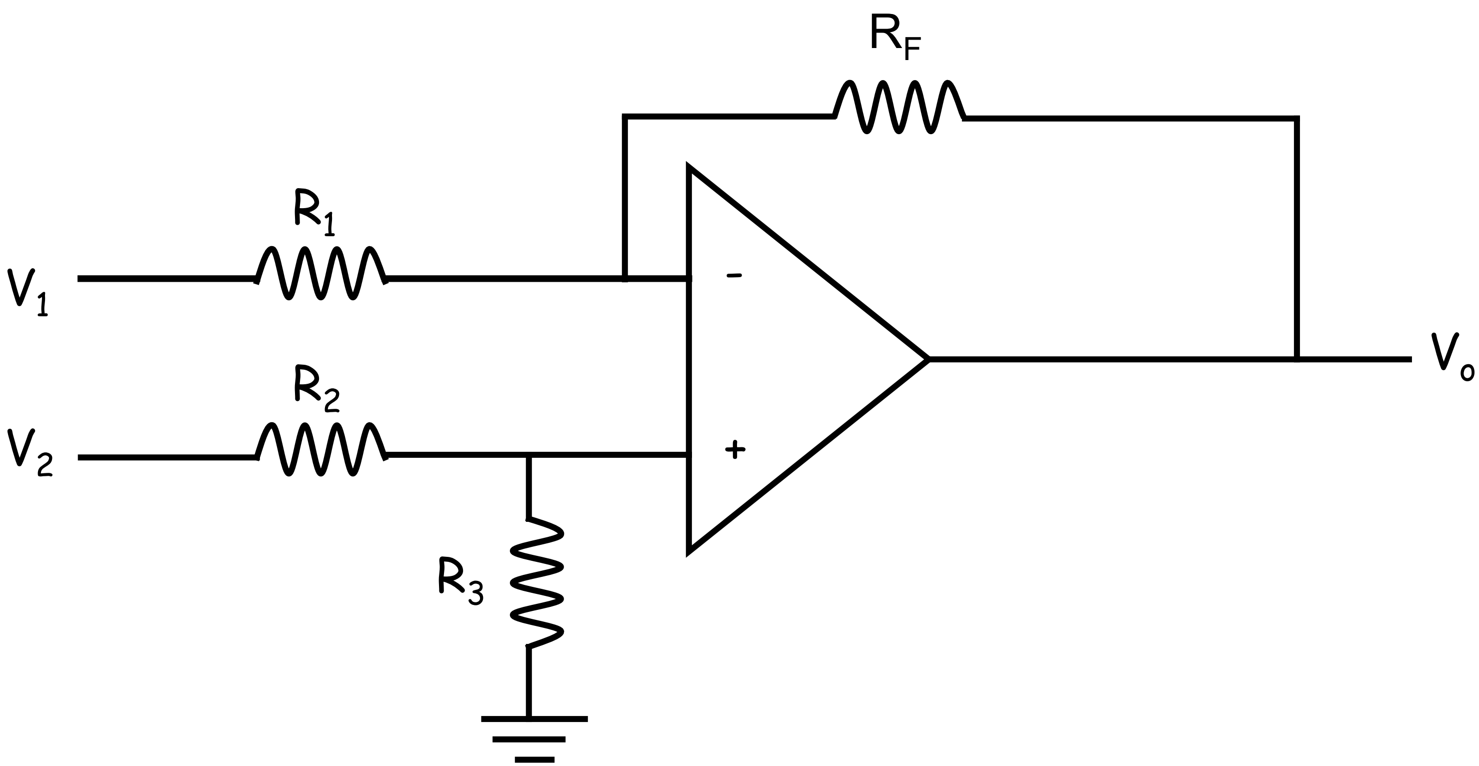
$$Av = V_o/V_i = [R_2 / R_1]$$

2. Inverse Adder



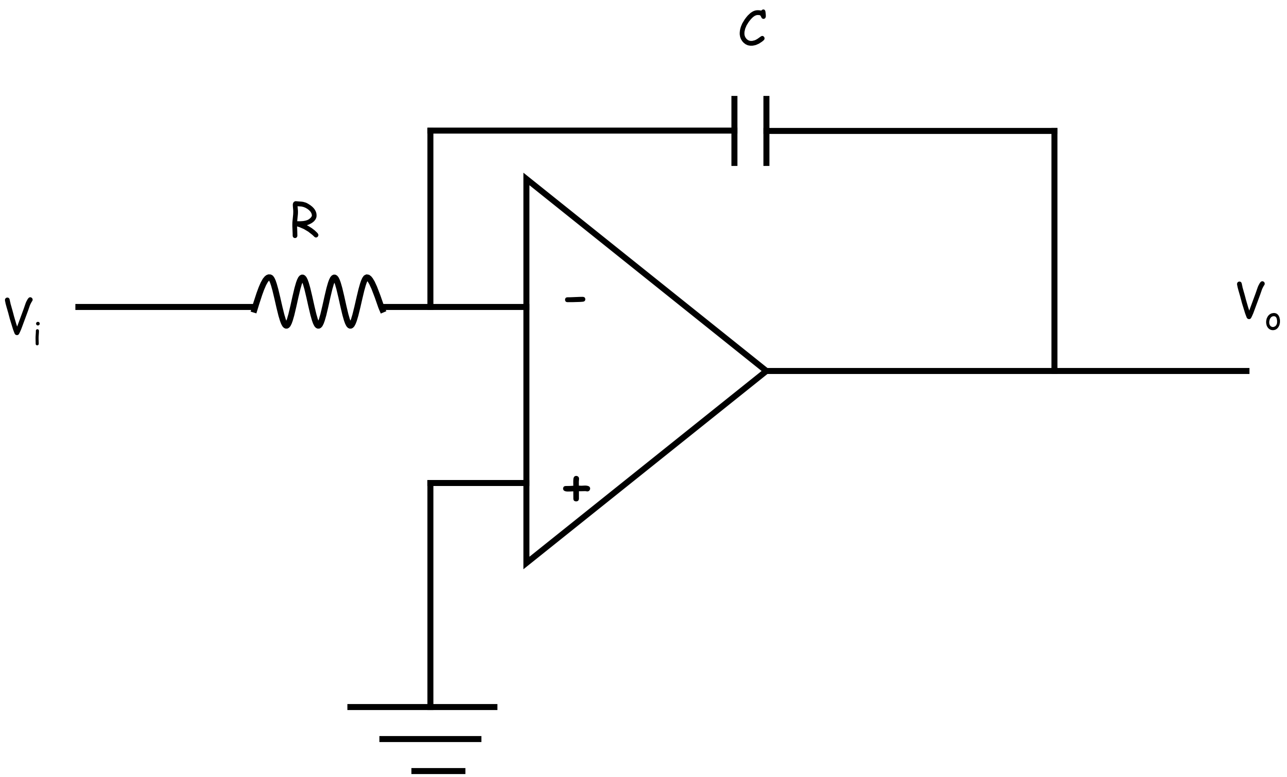
$$V_o = -[(R_F / R_1)V_1 + (R_F / R_2) V_2]$$

3. Subtractor



$$V_o = V_2 [R_3(R_F + R_1)/(R_1(R_2 + R_3)] - V_1(R_F/R_1)]$$

4. Integrator



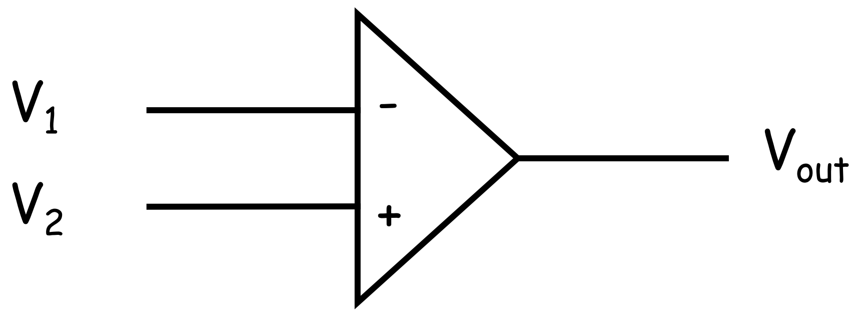
$$V_0 = -1/RC \int Vidt$$

7. Voltage Comparator

- **Output voltage (Vout) will become '1' logic and '0' logic base on the differences of the input (V_2-V_1).**
- **When (V_2-V_1) > 0, V_{out} = logic '1'**

or

$V_2 > V_1$, V_{out} = logic '1'
$V_2 < V_1$, V_{out} = logic '0' or
(V_2-V_1) < 0, V_{out} = logic '0'



INSTRUMENTATION AMPLIFIER

- Use to amplify small signal.
- Consists of a circuit that has three OP-AMP.
- The advantages of this type of instrument amplifier compared to standard OP-AMP are :
  i. Higher input resistance.
  ii. Better CMRR (common mode rejection ratio). CMRR is the ability of the amplifier to reject any identical signal from both input.

$$Zin \approx 300\ M\Omega \ \text{ to } \ 500 M\Omega$$

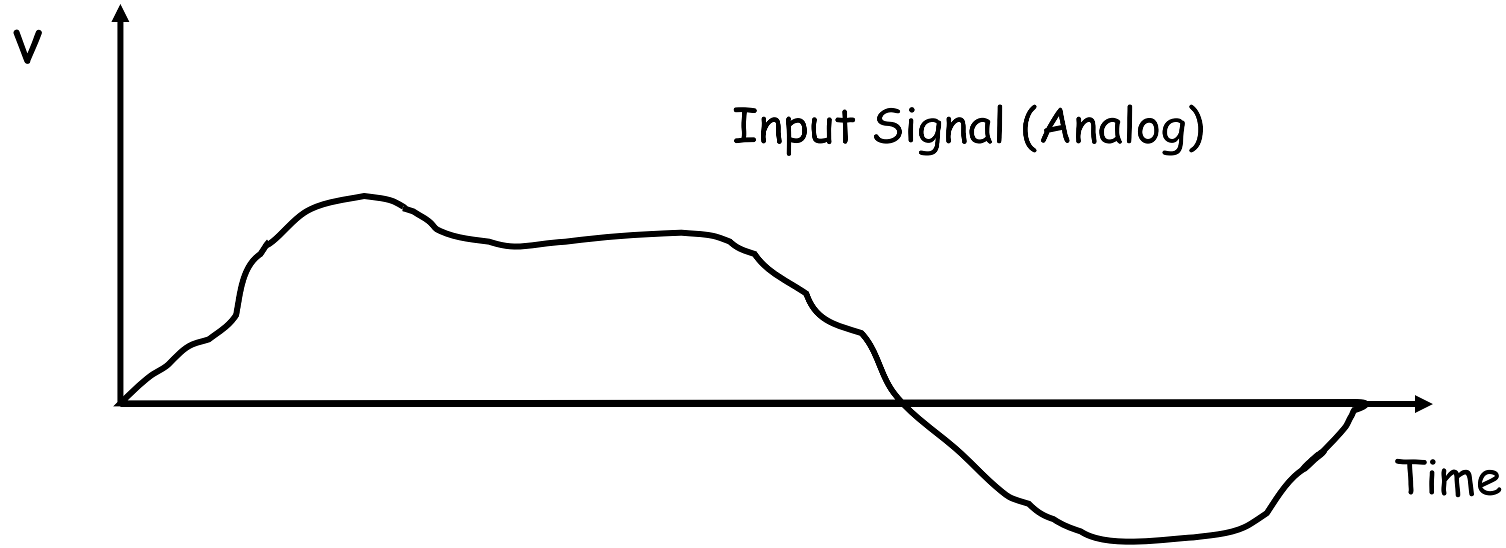
$$CMRR \approx 10^5$$

ANALOG-TO-DIGITAL CONVERTOR

- **Involve two operations, which are the sampling process and quantization process.**
- **Sampling operation is carried out by "sample-and-hold" device.**
- **Quantization process is carried out by the analog-to-digital convertor.**

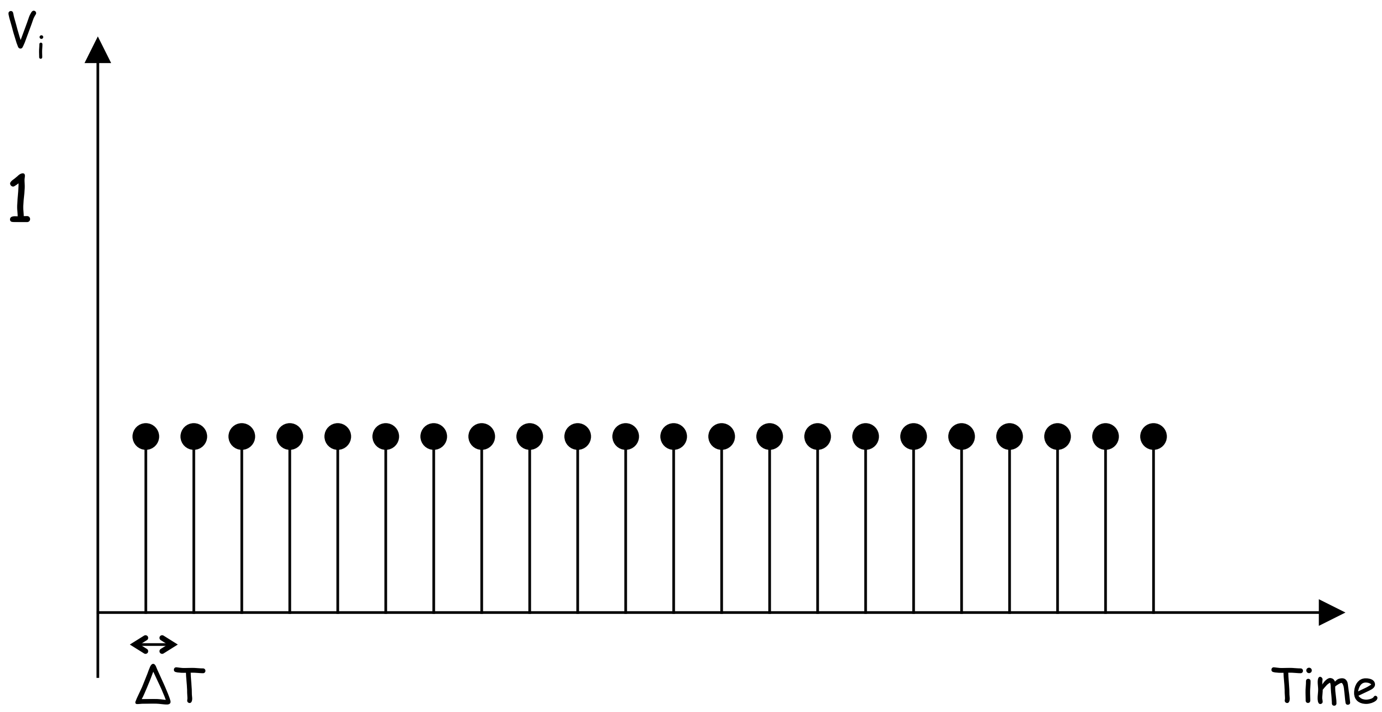
Example :

V(t) is a continuous signal (analog) which is received from the sensing element.



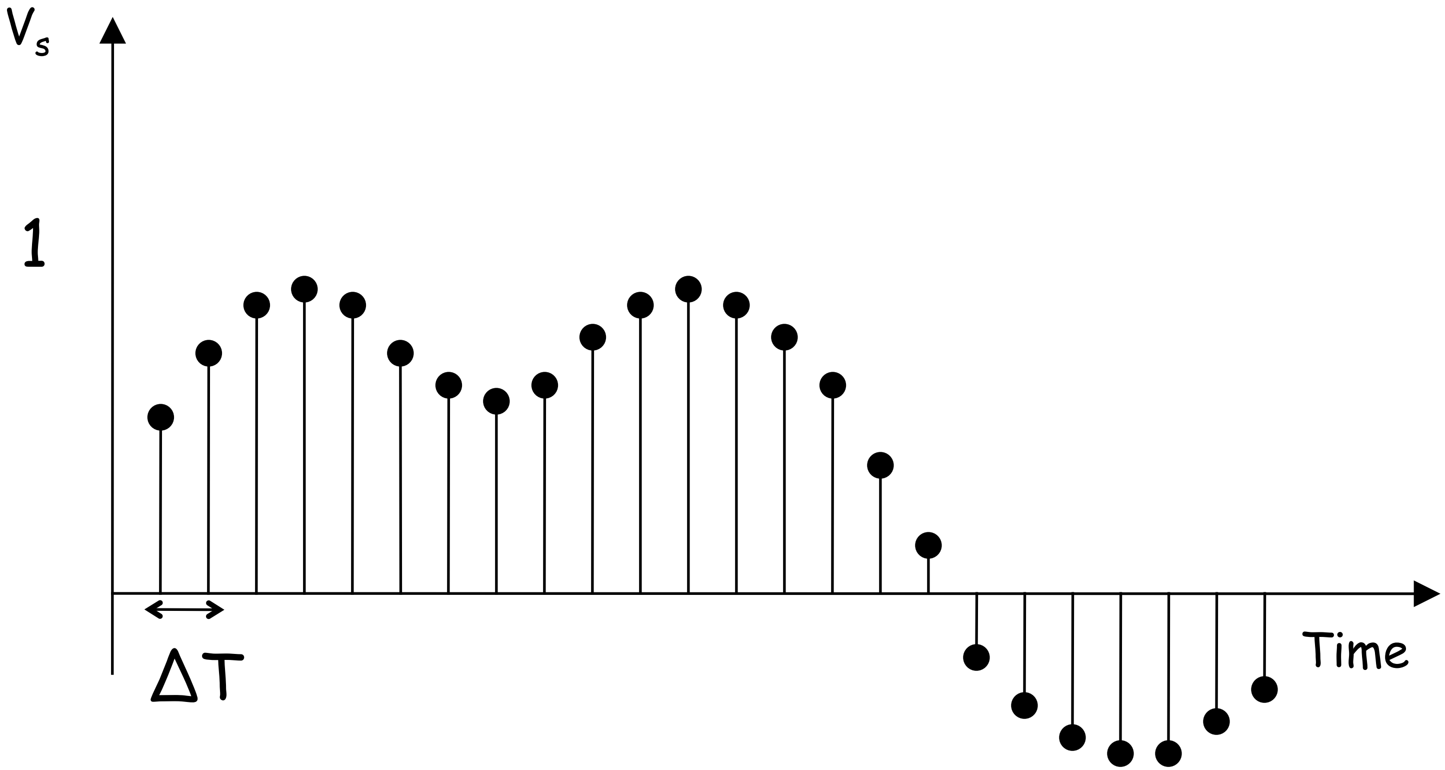
V(t) can be represented by a set of sample V_i where i = 1,2,3,4….. N taken at discrete interval DT (sampling interval).

Data sampling function



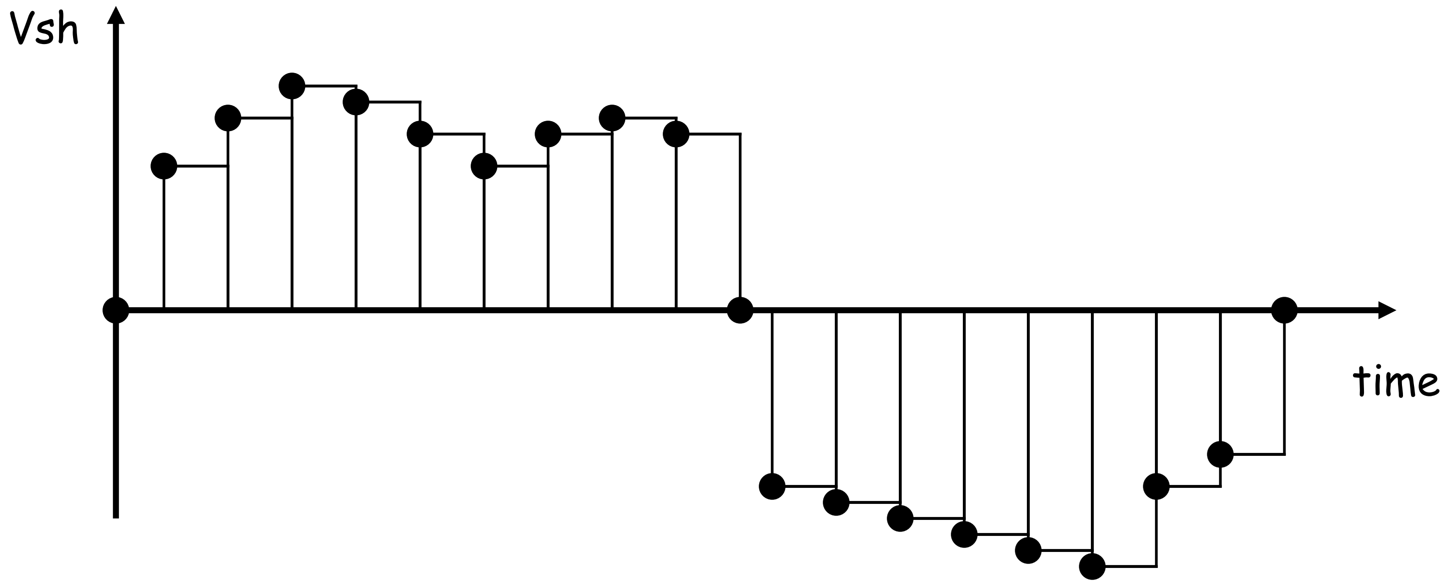
Sampling Frequency, fs = 1 ΔT

Sampled signal :



Sampling frequency, fs = 1 ΔT

- Since the operation of changing from analog to digital takes couple of miliseconds, output sample has to remain constant while waiting for the next change.
- Sampled and hold signal.



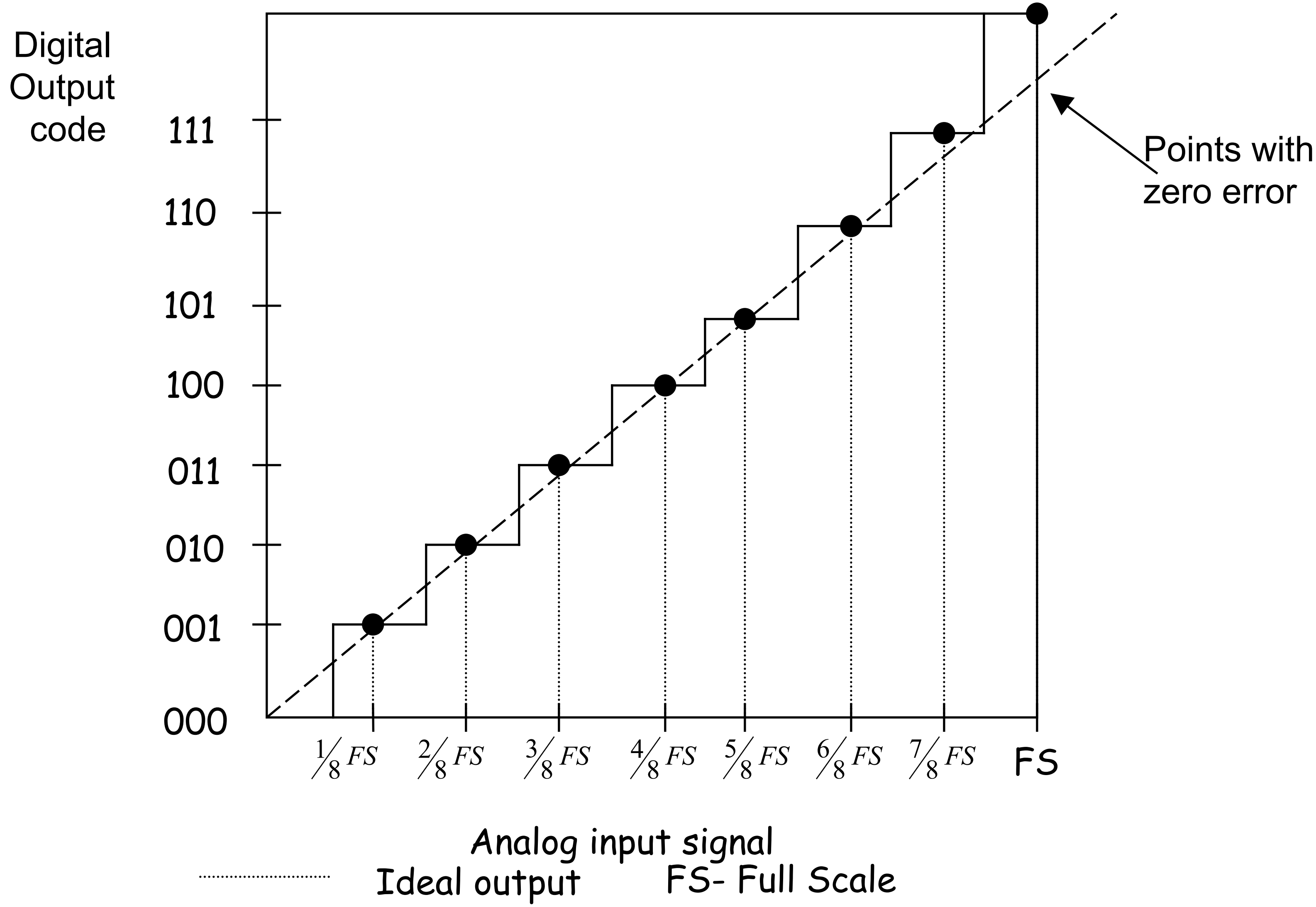
- Sample state : Input signal followed by output signal.
- Hold state signal : Output signal remains constant at input value during hold.

QUANTIFICATION PROCESS

- **A procedure when continuous analog signal is converted into few discrete levels.**
- **Analog input signal can be at any value between zero to full scale range.**
- **However, digital output signal can only be at finite number from output code where each number represents discrete level.**
- **Measurement resolution has to be considered in all digital measurement system.**

- **Resolution for analog-to-digital converter is the number of output state i.e number of output bits (n).**
- **Number of output = 2^n**
- **Transition = 2^n-1**
- **Resolution (in voltage) = ΔV = $\frac{FS}{2^n}$**
- **Quantization error (in voltage) = ± $\frac{\Delta V}{2}$**
- **where FS (full scale) is full scale voltage value.**

- **Graph showing the relationship between digital output and analog input for analog-to-digital 3-bits converter**



* Transition are exactly halfway between the points with 0 error

Example 1:

A 3-Bits converter Analog-to-Digital (ADC) has:

Number of output $= 2^3 = 8$

Transition $= 2^3 - 1 = 7$

Resolution $= \frac{FS}{2^3} = \frac{FS}{8}$

Quantization error $= \pm \frac{FS/8}{2} = \pm \frac{FS}{16}$

Example 2 :

Analog-to-digital 4-bits converter has ± 1/2 bits of quantization error and 5 volt of input full scale voltage. Calculate the quantization error in volt and accuracy percentage (full scale) of the instrument.

Resolution $= \Delta V = \dfrac{FS}{2^n} = \dfrac{5V}{2^4} = 0.3125$

Quantization error $= \pm \frac{1}{2}\text{ bit} = \pm \dfrac{\Delta V}{2}$

Percent accuracy $= \pm \dfrac{0.15625\text{ V} \times 100}{5V} = \pm 3.125\%$

SIGNAL SAMPLING

- **Digital system received input signal (in analog form) through the sampling process where the received data are in 'discrete' signal.**
- **Digital signals are different with the analog signal. Differences can be minimise by selecting suitable time sampling, which is:**

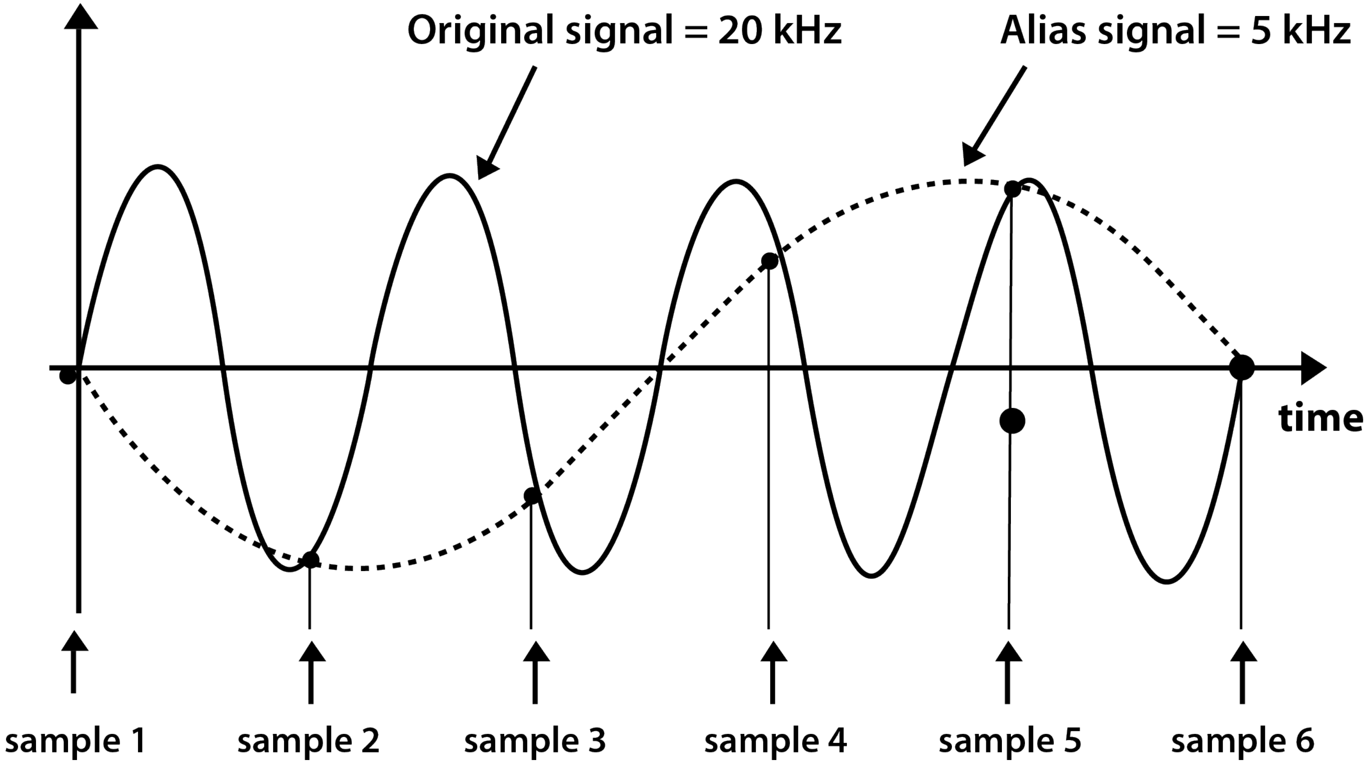
$$fs > 2 \times fa \qquad \text{[Nyquist Law]}$$

where, fs : sampling frequency

fa : actual frequency

- **If the sampling frequency (fs) is lower compared to the original frequency (fa), aliasing will occur.**
- **“Aliasing” will cause the “actual frequency” cannot be displayed appropriately.**

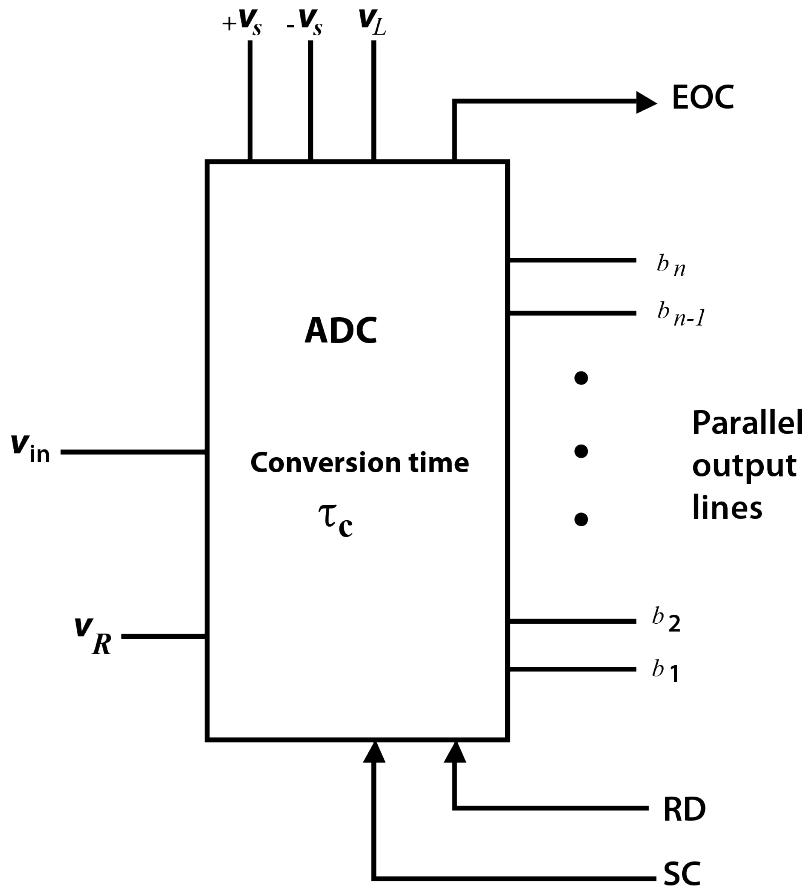
Aliasing Effect



Sample Rate = 25 kHz

Generic ADC diagram

A generic ADC diagram, showing typical input dan output signals and noting the conversion time



The following list summarizes the important characteristics of the ADC.

- *Analog voltage input:* This is the for connection of the voltage to be converted.
- *Power supplies*: Generally, an ADC requires voltage supply for internal op amps.
- *Digital outputs*: the converter will have *n* output lines for connection to digital interface circuitry.
- *Control lines*: the most common lines are: *SC* (start convert), *EOC* (end of convert), *RD* (read)
- *Conversion time*: the ADC must sequence through a process to find the appropriate digital output and this process takes time.

CONVERSION FROM ANALOG TO DIGITAL SIGNAL or vice versa

- **Large numbers of practical problems are solve by using combination of two techniques :**

  1. **Analog-to-digital converter or ADC**
  2. **Digital-to-analog converter or DAC**

Types of ADC :

- Single Ramp ADC
- Successive Approximation ADC

I. Single Ramp ADC

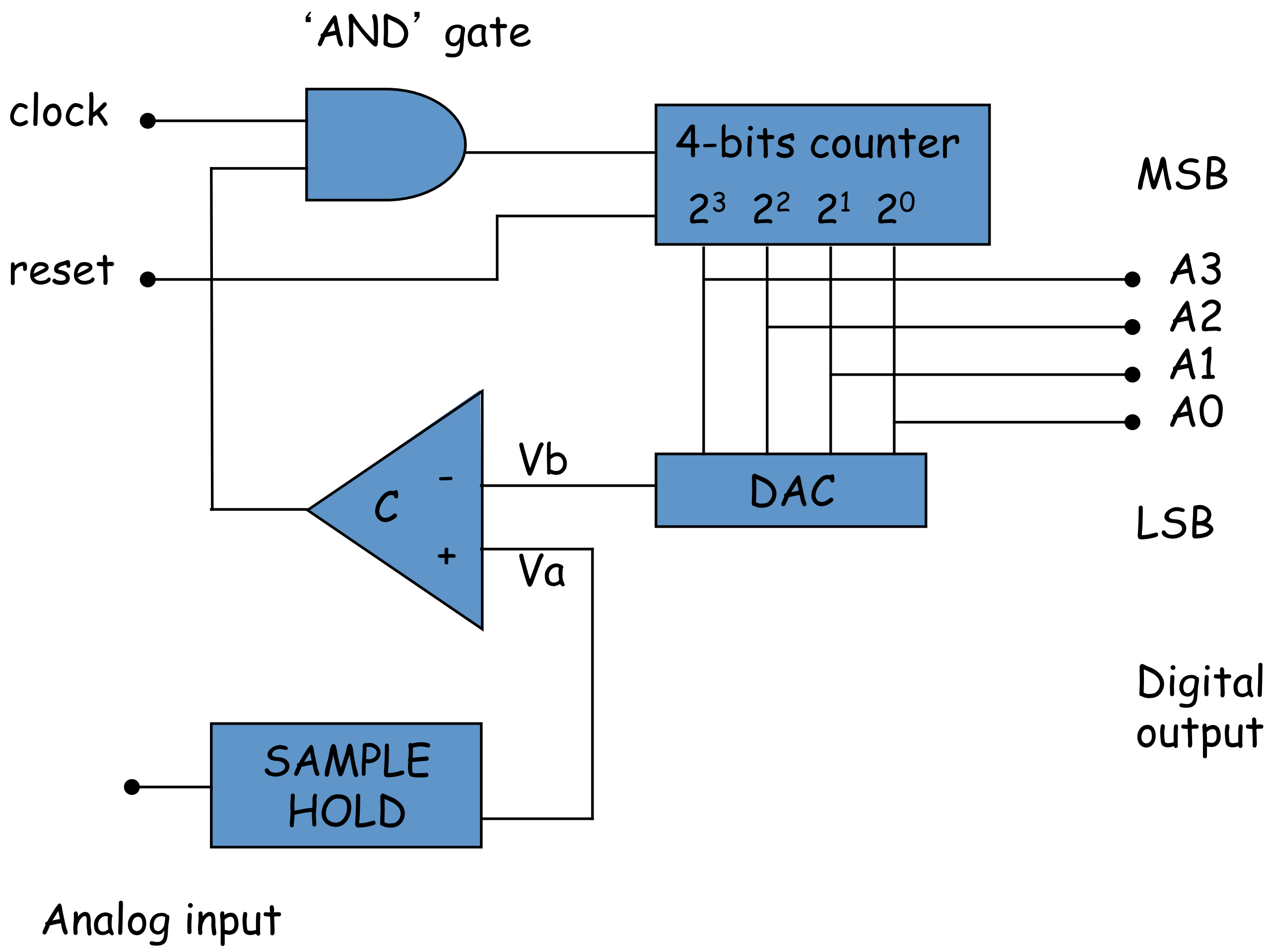
- <u>**Single Ramp ADC**</u>

- **Employ a simple method.**
- **Uses three main elements:**

1. **Counter**
2. **DAC**
3. **Analog Comparator.**

Operation Principles

- During the initial cycle, counter is reset to 0.
- Analog input is put into sample-hold circuit where the output is fed into the comparator.
- Output from the comparator will become “1” logic or “0” depending on the comparison between the 2 inputs.
- Counter will count upwards until the output from the comparator becomes “0” logic where the counter will stop counting.
- Comment
- This counter operation is considered slow as it needs longer time if the number of bits increased.



Simple Ramp ADC

Example 1:

Analog input = 5V

Step	Comparison	Answer	Digital output
Reset system			0000
1	Va > 0?	Y	0001
2	Va > 1?	Y	0010
3	Va > 2?	Y	0011
4	Va > 3?	Y	0100
5	Va > 4?	Y	0101

Therefore, digital output = 0101 (5 times of cycle needed)

Example 2 :

Analog input = 3 V

Step	Comparison	Answer	Digital output
Reset system			0000
1	Va > 0?	Y	0001
2	Va > 1?	Y	0010
3	Va >2?	Y	0011

Therefore, digital output = 0011 (3 times needed)

ii. Successive Approximation ADC

- This type of ADC is often be used.
- Has constant conversion time i.e. similar time scale for any analog input.
- Consists of “successive approximation register” (SAR), DAC and comparator.

Operation Principles

- **Analog input is checked whether the value is smaller or bigger than DAC output.**
- **If the analog input value is bigger than (P), byte in SAR remain as 1 logic.**
- **If the analog input value is smaller than (<), byte in SAR is reset to 0 logic.**
- **HIGH SOC value will start the overall conversion process where each byte will be set or reset and next, tested.**
- **When the conversion ends, control circuit will transmit the signal to EOC so that the digital number will be sent to a buffer register.**

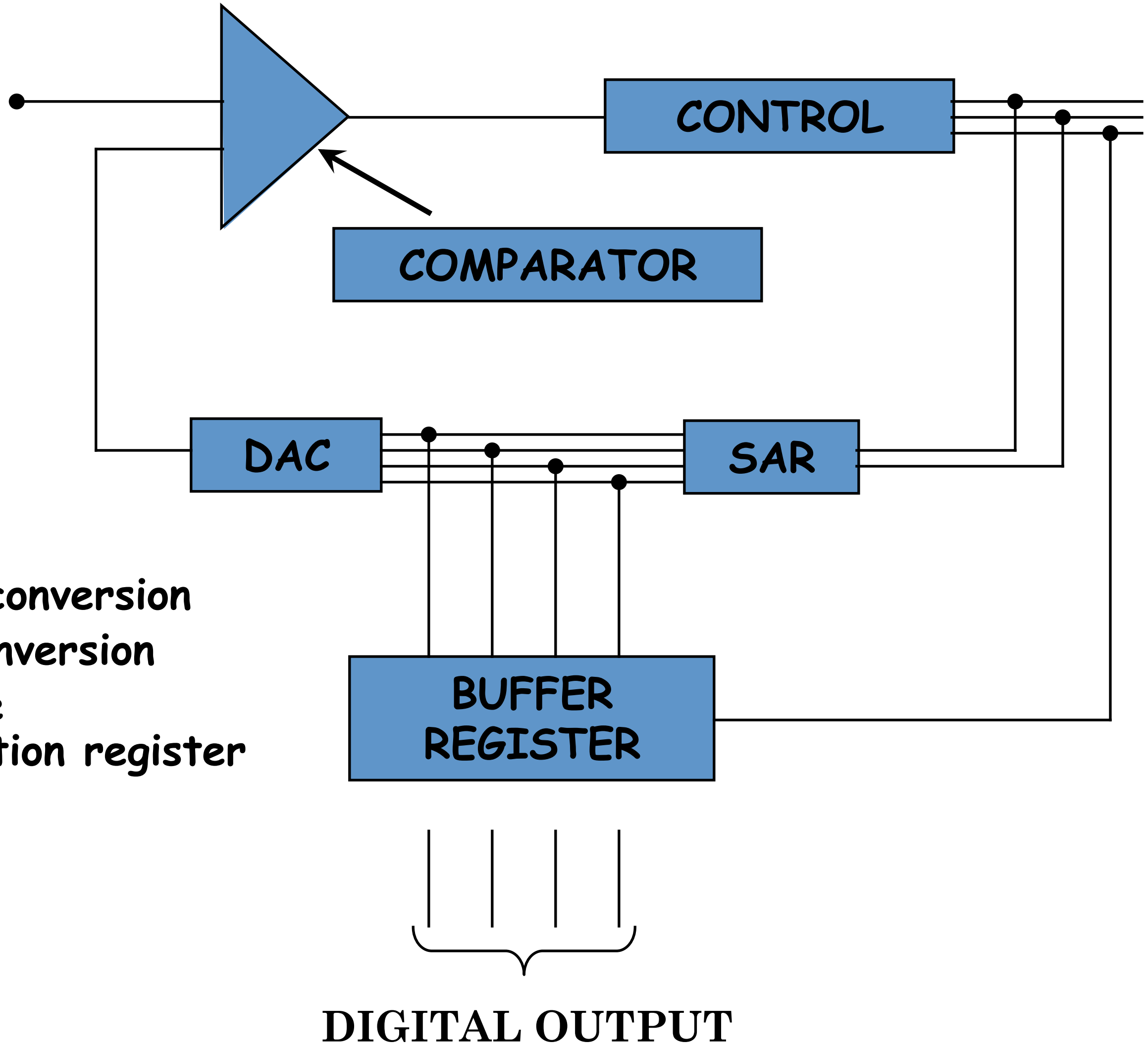
Example 1 :

Analog input = 10 V

Step	Comparison	Answer	Digital answer (YES=1,NO=0)
1	Va P 8?	YES	1 (MSB)
2	Va P 12?	NO	0
3	Va P 10?	YES	1
4	Va P 11?	NO	0 (LSB)

Therefore, the digital output is = 1010

The Successive Approximation ADC



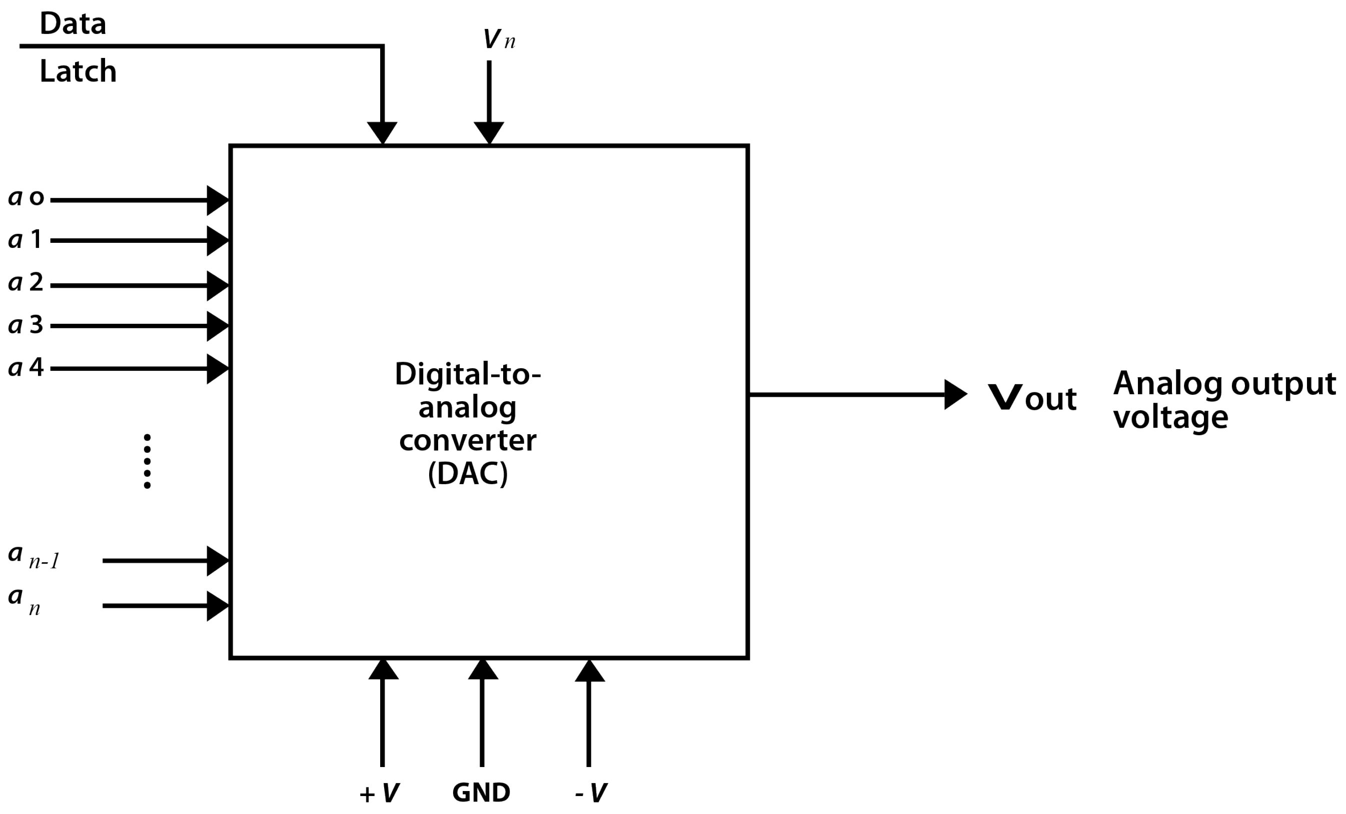
SOC : start of conversion
EOC : end of conversion
SAR : successive approximation register

DIGITAL-TO-ANALOG CONVERTER OR DAC

- **Signal processing often use digital system and the signal is converted back to analog signal for further process.**
- **DAC is the interface between analog devices and digital devices.**

Generic DAC diagram

A generic DAC diagram, showing typical input and output signals



The following list summarizes the important characteristics of the DAC.

- *Digital input*: is a binary word composed of a number of bits specified by the device.
- *Power supply*: is required
- *Reference supply*: a reference supply is required to establish the range of output voltage and resolution of the converter.
- *Output:* the output is a voltage representing the digital input. This voltage changes in steps as the digital input changes by bits.
- *Data latch*: when a logic command is given to latch data, whatever data are on the input bus will be latched into the DAC, and the analog output will be updated for that input data. The output will stay at that value until new digital data are latched into the input.
- *Conversion time*: a DAC performs the conversion of digital input to analog output virtually instantaneously.

Types of DAC :

i. Weighted Resistor DAC

- Consists of references voltage, binary switches, weighting network and summing/adder amplifier.
- Resistors used are related to each other by the power of 2 factor where:

LSB	$R_0 = R/2^0 = R$
(Least Significant Bit)	$R_1 = R/2^1 = R/2$
MSB	$R_2 = R/2^2 = R/4$
(Most Significant Bit)	$R_3 = R/2^3 = R/8$

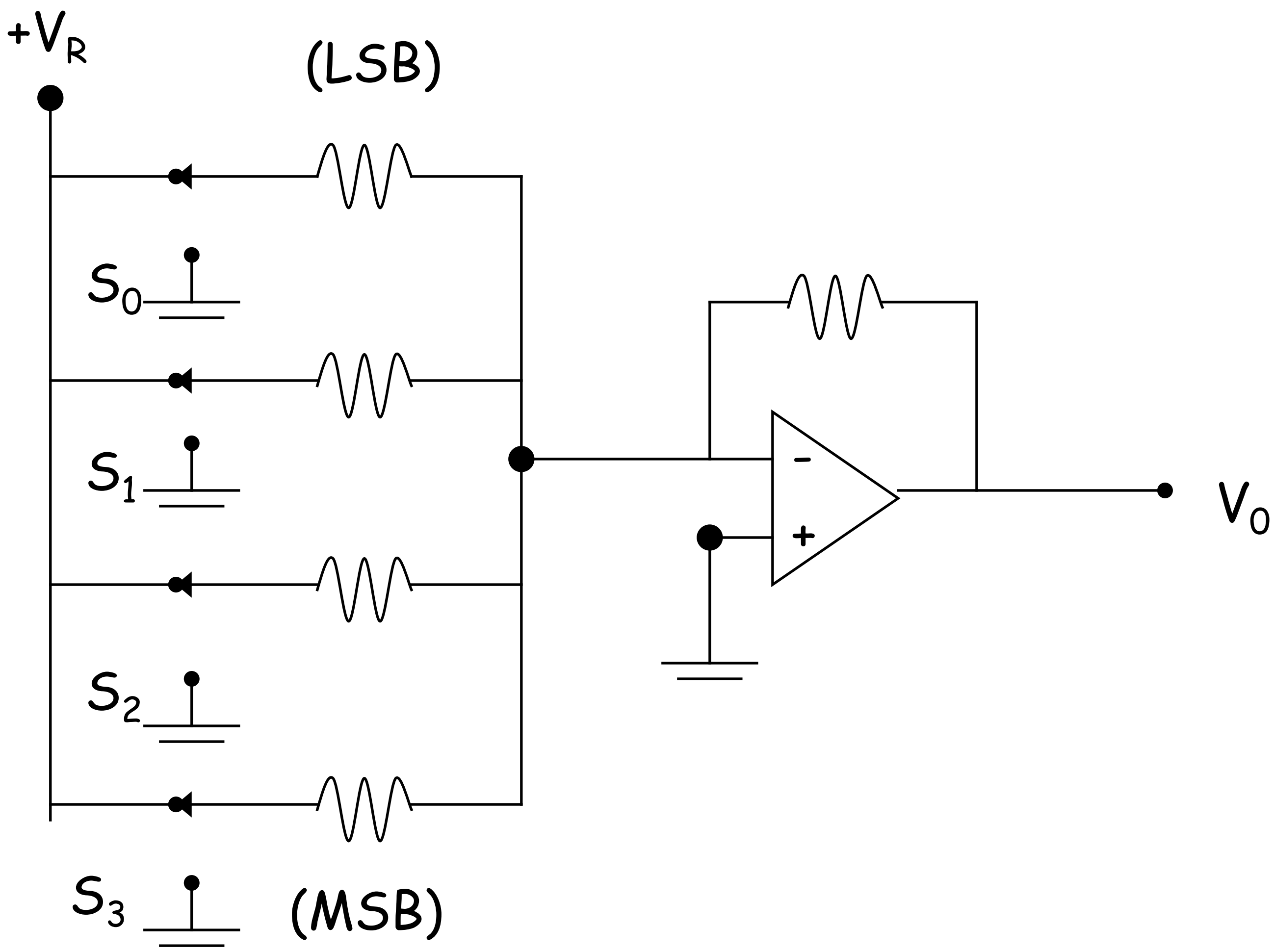
- **V_0 value can be calculated from this equation:**

$$V_0 = \frac{(-R_f \cdot V_R)}{R} \left[2^3 S_3 + 2^2 S_2 + 2^1 S_1 + 2^0 S_0\right]$$

- **Where, Si = logic "1" when the switch is "On" logic "0" when the switch is at "Off" position.**

Limitation :

- Accuracy and stability of DAC rely on the resistor value R which is divided by the power of 2 factor and it's ability to track each other.
- Error in the voltage value is when the first resistor value R differs from the specified range.
- This type of DAC is suitable for low resolution system.



Weighted Resistor DAC

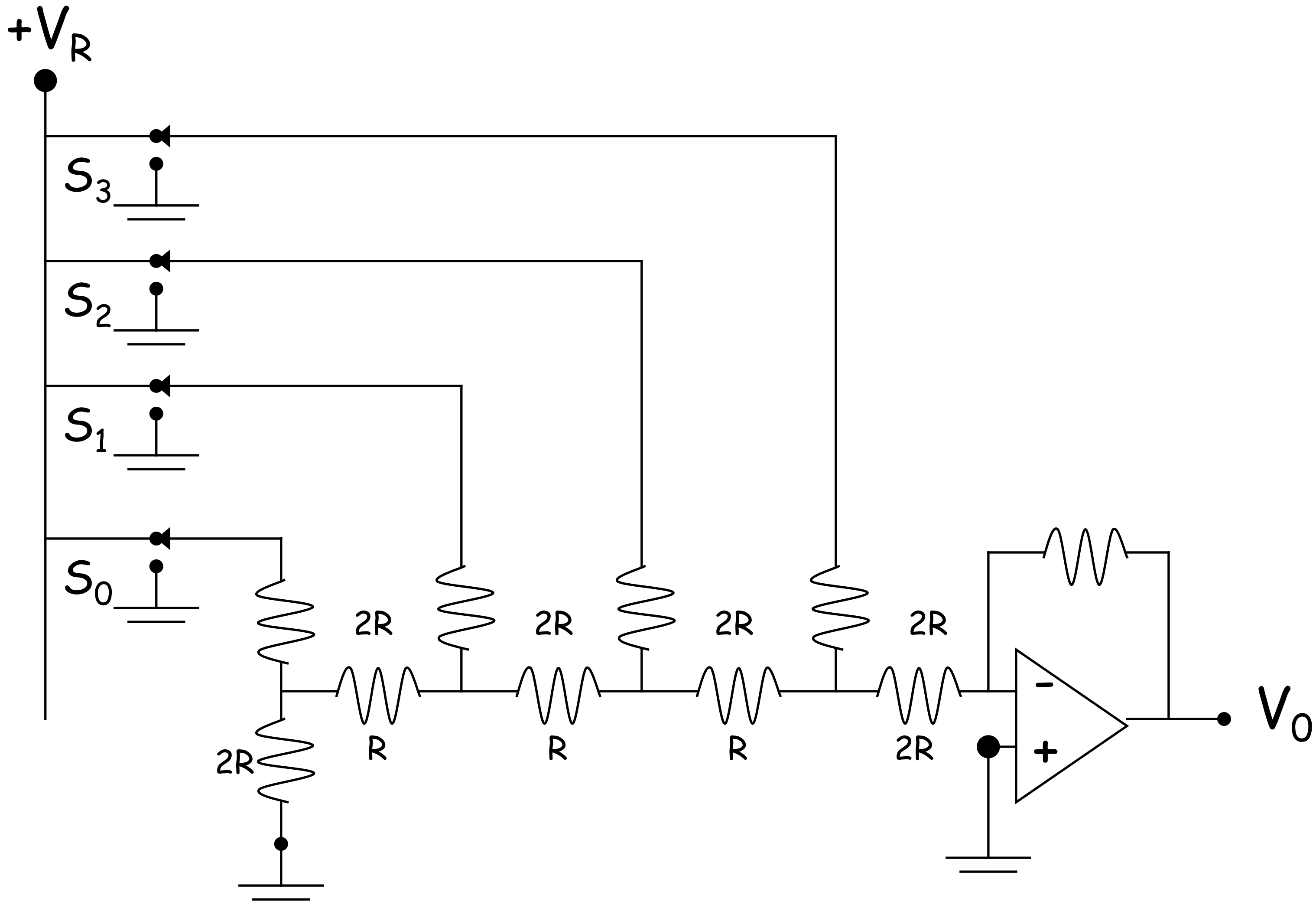
ii. R-2R Ladder DAC

- This type of DAC uses only small resistor's range where only 2 resistor values R and 2R are employed.
- Resistance ladder can be obtained in one package.
- V_0 can be obtained from:

$$V_0 = \frac{(-R_f \cdot V_R)}{48R} \left[2^3 S_3 + 2^2 S_2 + 2^1 S_1 + 2^0 S_0\right]$$

- where, Si = logic "1" when the switch is at "On"

logic "0" when the switch is at "Off" position.



The R – 2R Ladder DAC

FILTERS

- The functions are :
  1. To select the required frequencies from input signal.
  2. To eliminate the non-required frequencies from the input signal.
  3. To choose certain required group of frequencies from the input signal.

Passband **: certain group of frequencies freely able to pass the filter.**

Stopband **: certain group of frequencies freely unable to pass the filter freely.**

Transmission **: Frequency transportation process. The amplitude of the frequency remains before (input) and after (output). In practice, -3 dB (decibel) is the point when the signal starts to weaken.**

Attenuation **: The concept is opposite of transmission. Attenuation is when the signal amplitude starts to reduce to –3 dB compared to the initial signal.**

TYPES OF FILTER

- **Low pass Filter (LPF)**
- **High pass Filter (HPF)**
- **Band pass Filter (BPF)**
- **Band stop Filter (BSF)**

1. Low pass Filter

- Consists of circuits allowing low frequency and disallow higher frequency from passing through the filter.
- Designed to send frequency values from zero to cut-off frequency (f_c) without attenuation.
- Frequencies higher than fc will be cut-off.

2. High Pass Filter

- Consists of circuit which allow only high frequencies to pass through the filter.
- Transmit all frequencies which is between fc and infinity.
- Frequency below f_c will be eliminated.

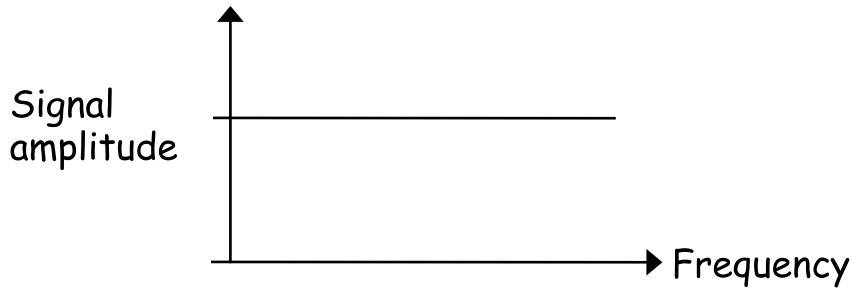
3. Band Pass Filter

- **Consists of circuits that allow only certain group of frequencies to pass through the filter.**
- **It is designed to send frequencies between 2 cut-off frequencies which are f_{c1} or f_{c2} ; whereas frequencies below f_{c1} or above f_{c2} will be eliminated.**

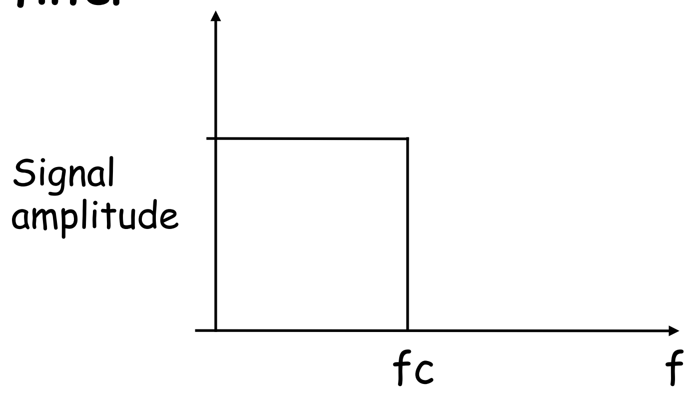
4. Band Stop Filter

- This filter allows all frequency to pass through except for a group of specific frequency (stopband).
- Also knows as band-attenuation/ band elimination filter and the function is opposite BPF.
- It is designed to allow frequencies less than f_{c1} and bigger than f_{c2}.

a. Raw signal

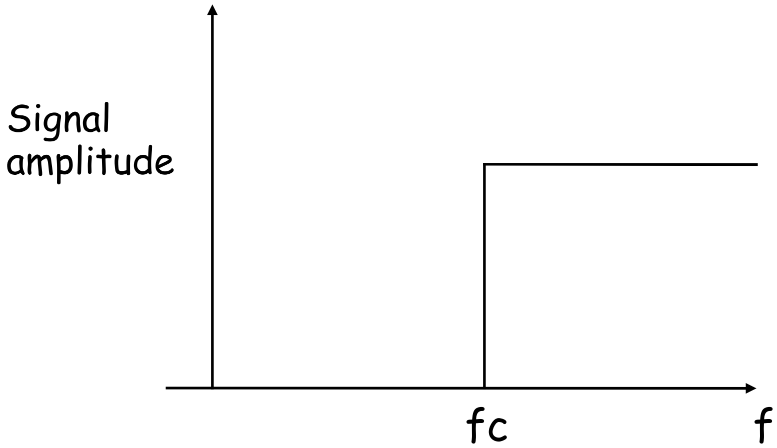


b. Low-pass filter

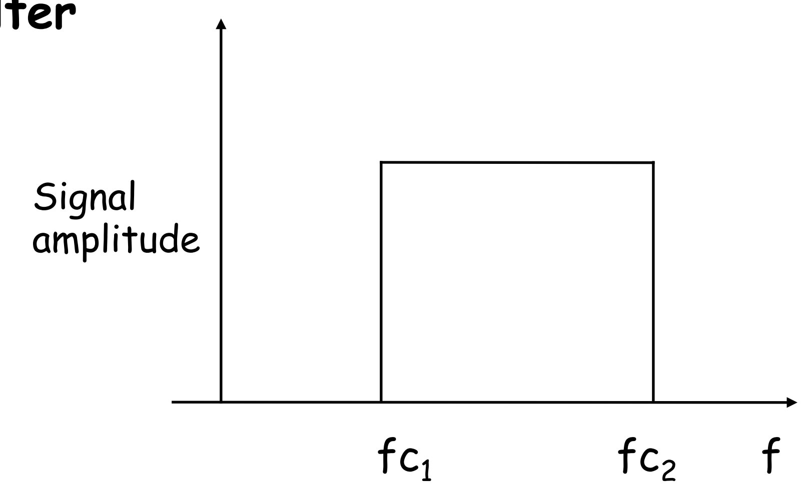


OUTPUT FROM IDEAL FILTERS

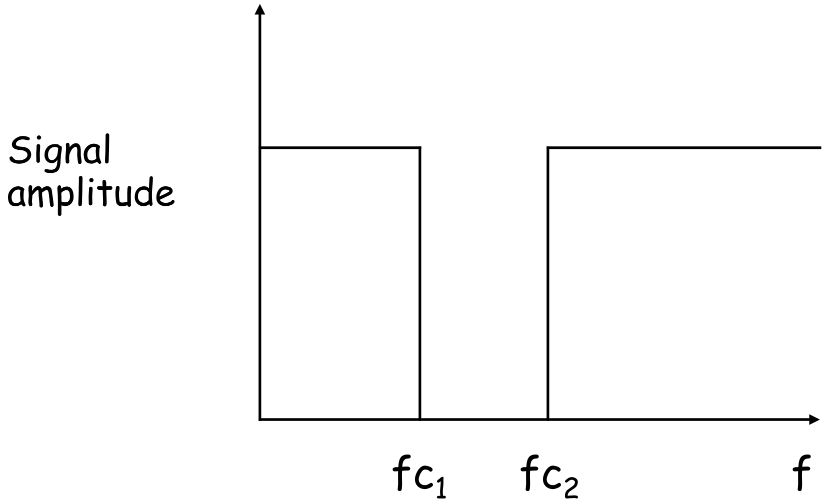
c. High-pass filter

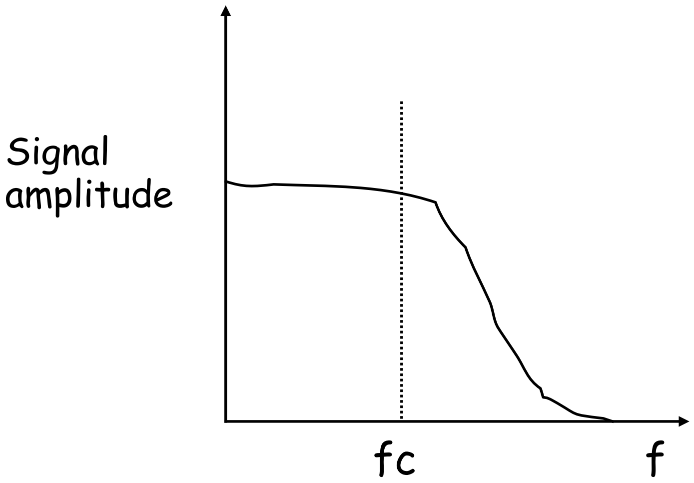


d. Band-pass filter

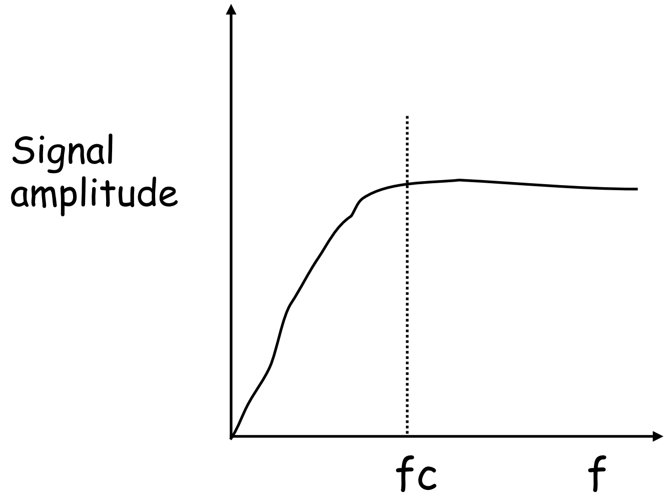


e. Band-stop filter

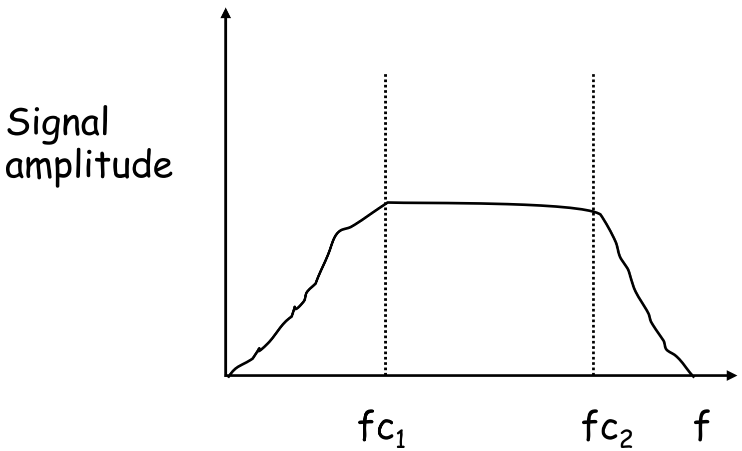




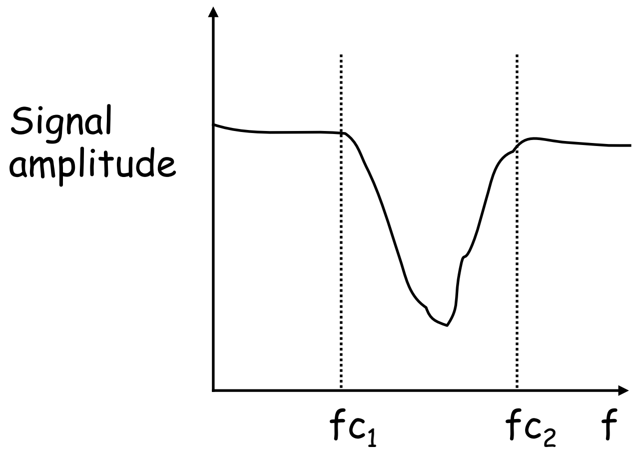
a. Low-pass filter



b. High – pass filter



c. Band-pass filter



d. Band-stop filter

OUTPUT FROM PRACTICAL FILTERS

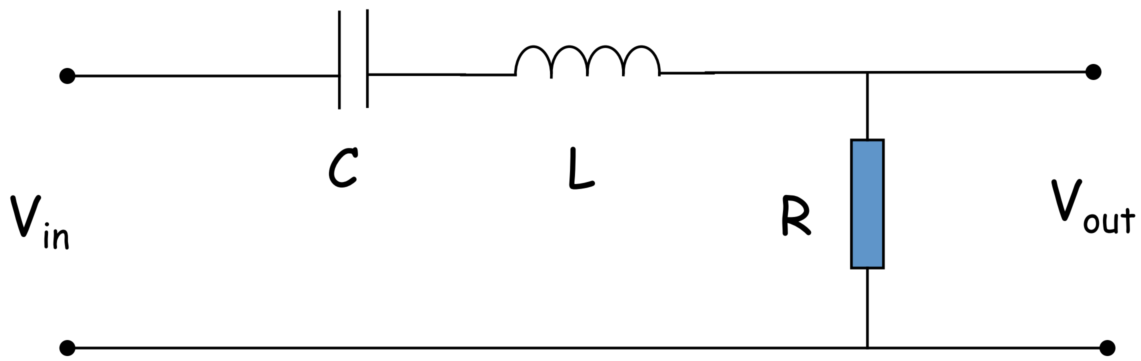
RC FILTERS

- This type of filter is a combination of resistors (R) and capacitors (C).
- Capable of allowing certain parts of signal to pass through the filter, besides disallowing unnecessary signal.

RLC FILTERS

- This type of filter is a combination of a resistor (R), inductor (L) and capacitor (C)

1. Band-Pass Filter (BPF)



- Filter allows signal at f_r (resonant frequency) and frequency range below and above the f_r value where f_r is :

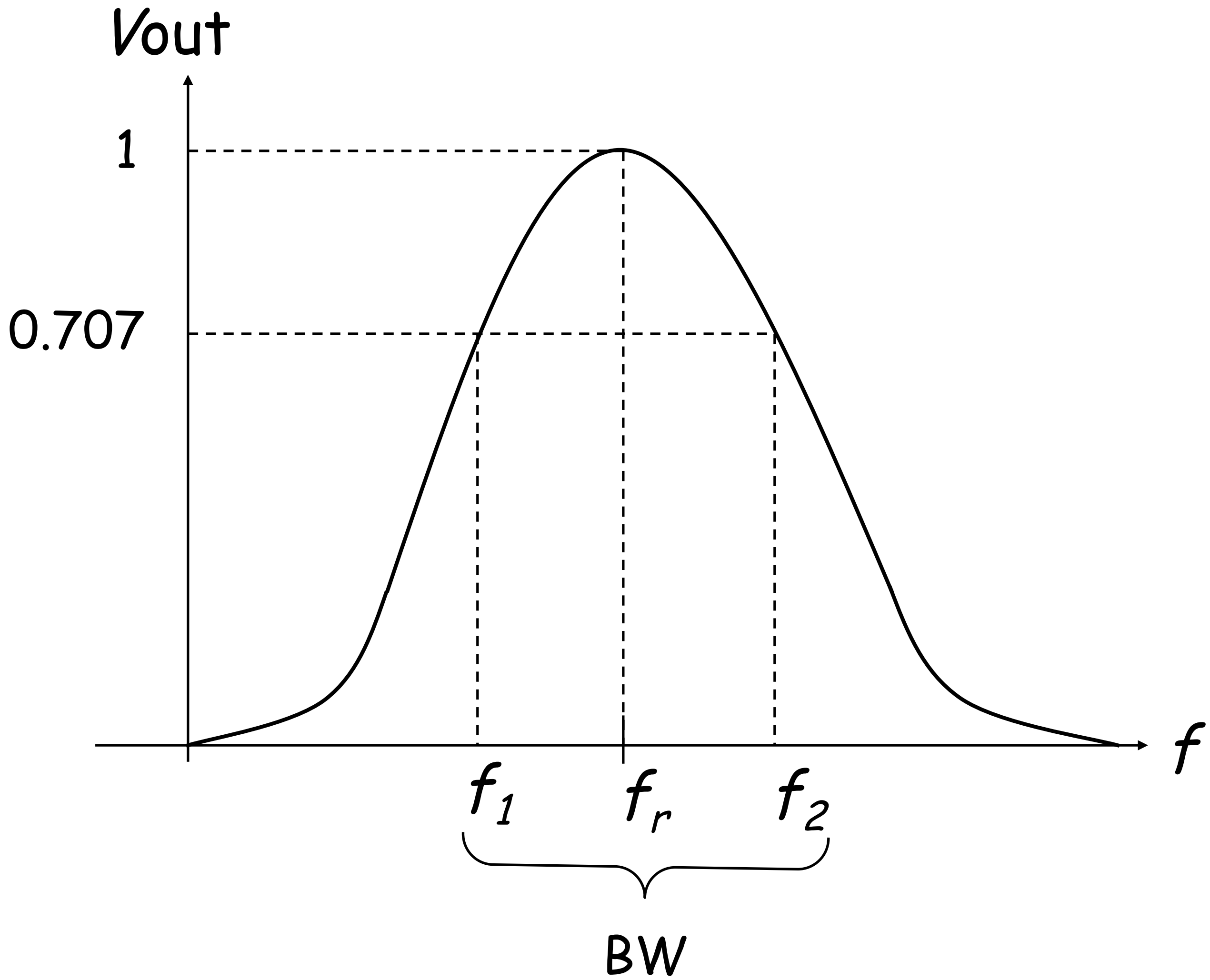
$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

- **Bandwidth (BW) this filter is the frequency range when filter output is –3 dB.**

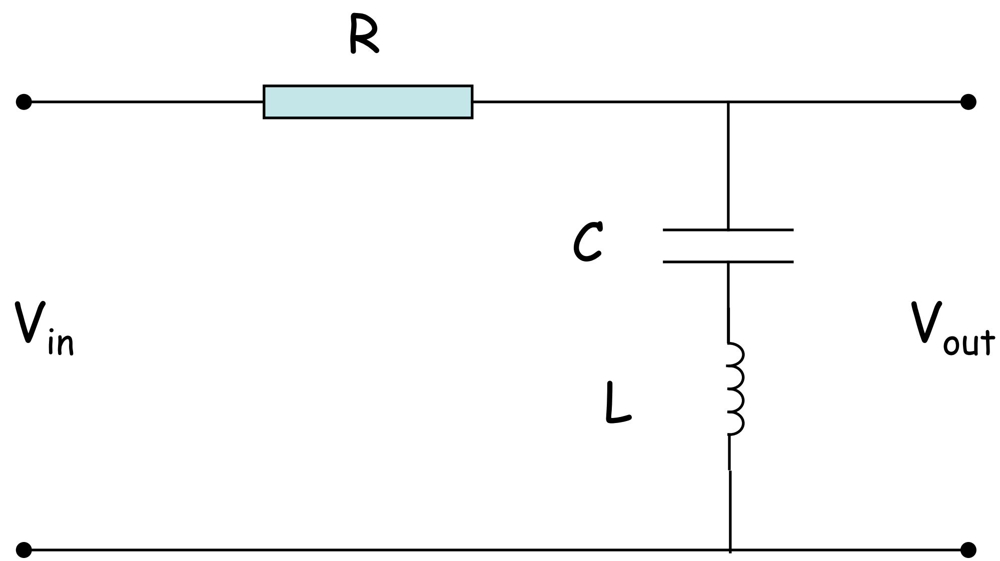
$$BW = f_2 - f_1$$

where, f_1 : lower cut-off frequency

f_2 : upper cut-off frequency


Vout
1
0.707
f
f1
fr
f2
BW

2. Band-Stop Filter (BSP)



- This filter eliminates the signal in between the upper cut-off frequency (f_2) and lower cut-off frequency (f_1) where :

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

NOISE

- Generally, noise is defined as any unwanted signal that is not originated from/to - with input signal.
- Noise cannot be eliminated totally.
- There are two types of noise, which are internal and external.

1. External Noise

- Noise that originated from outside of system's component.

  Example :

i. Atmospheric Noise – thunder, lightning

ii. Man-made Noise – from man-made instrument or system e.g. motor.

2. Internal Noise

Noise that is originated from inside of system's component etc.

Example :

1. **Thermal Agitation Noise**

   Noise produced by resistor component caused by random motion of charged particle which is the electron in conductor.

   This type of noise can be found in all electronic circuits which use resistor.

2. **Shot-Noise**

   Can be found in all amplifying devices and is caused by the current flow in the electronic component i.e transistor.

SIGNAL-TO-NOISE ratio

- Use to compare noise and signal so that excessive noise will not occur.
- A good signal will have a high value of SNR.

$$SNR = \frac{Signal}{Noise}$$

SIGNAL TRANSMISSION

- When a measurement variable need to be sent to other location, such as control room, transmission element is needed.
- Signal transmission elements can be categorized into:

1. Cable type

   Data is transformed through wire.

2. Radio Frequency type

   Data is transferred using radio waves.

Data Transmission

- Digital signal is compatible with the computer system where certain converter is not sufficient.
- Signal can be transmitted by parallel or series.
- A digital information which is transmit out/in or into computer system is called word (16 bits).

Parallel Transmission

- **Data is transmitted simultaneously.**
- **Information bits is send at the same time.**
- **Different transmission line is use for each bits in computer language.**

Example: **1011 ----> 1011**

Series Transmission

- Information bytes will be send one by one through a transmission line.
- Advantage : need only one transmission line.
- Disadvantage : slower process compared to parallel transmission.
- *Example :* 1011 --→ 1

0

1

1