ME3200 ELECTRONIC INSTRUMENTATION AND MEASUREMENT

dream CATCHER

http://dreamcatcher.asia/cw

5. Analog Signal Conditioning

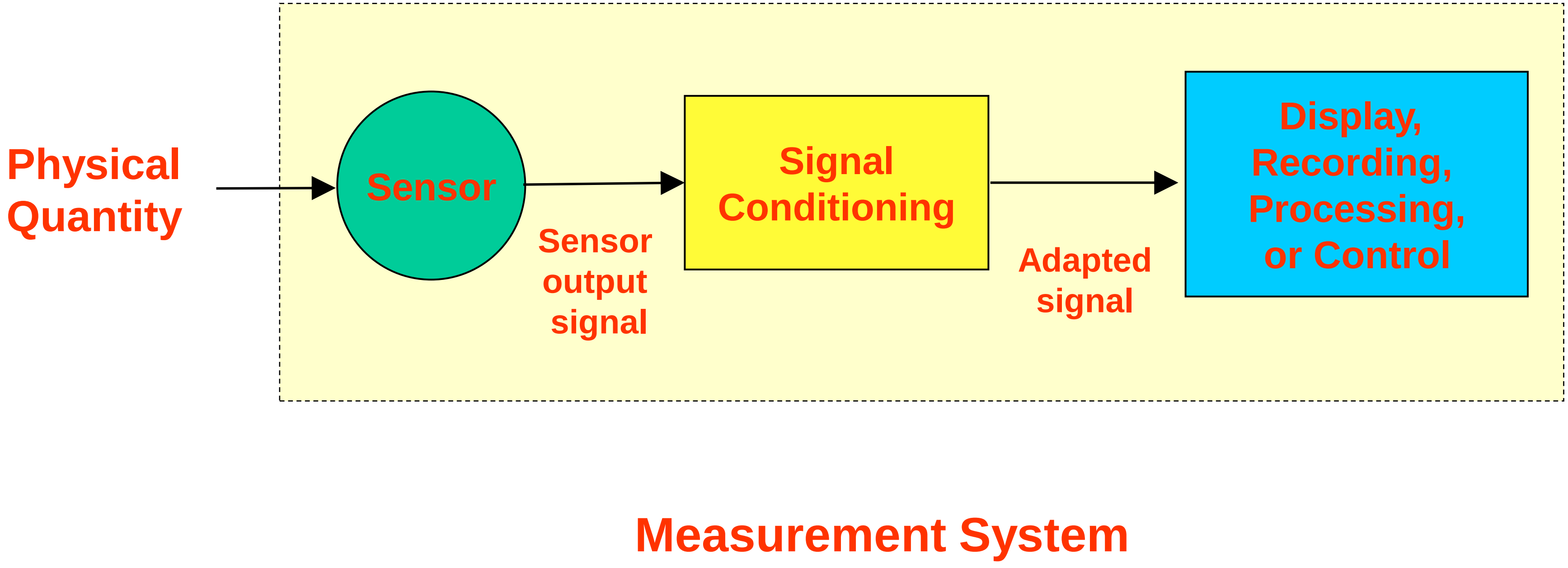
Contents

- Introduction
- Common Signal Conditioning Processes
- **Operational Amplifier**
  - Op-Amp Signal Conditioning Applications
- **Analog Filters**
- **Signal Conversion**
  - Resistive Sensor Signal Conditioning
  - Reactive Sensor Signal Conditioning
- **Input Circuit Protection**
  - Opto-Coupling
  - Isolation Amplifier
- **Analog to Digital Conversion**

Introduction

- The output signal from a sensor usually does not have the suitable characteristics for displaying, recording, transmission, or processing.
- Common issues with the sensor output signal:
  - **Low amplitude**
  - **Contains noise**
  - **Not in the voltage or current form to be directly interpreted by electronics systems**
  - **In analog form, the signal cannot be recorded or processed by digital systems**
- **Signal conditioning**: the processing of the sensor signal to adapt the signal to the requirements of the next stage in a measurement system.
- **Signal conditioner**: the interfacing circuit between the sensor and the data recording or processing system that performs the necessary signal adaptation.

Signal Conditioning in Generalized Measurement System



Common Signal Conditioning Processes

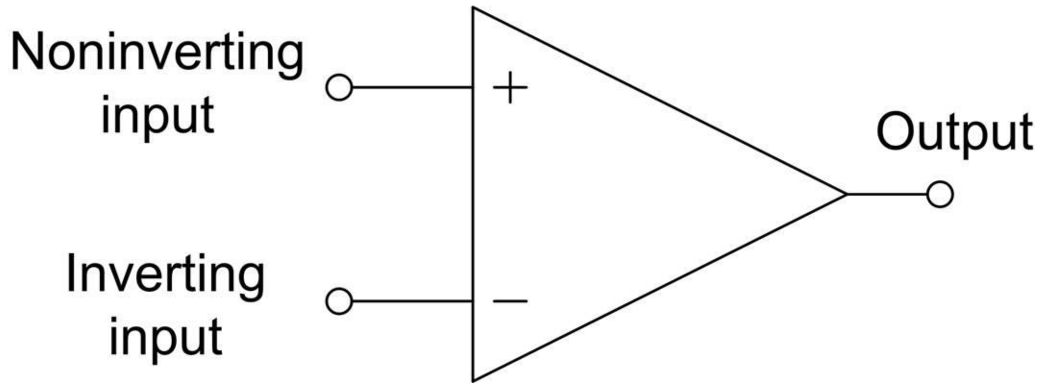
- **Amplification**: to magnify the signal to a suitable level, matching the input range of the next stage in the measurement system.
- **Filtering**: to reduce the signal components in the unwanted frequency ranges (noise or interference rejection).
- **Signal Conversion**: to convert the sensor output signal into a suitable form for the next stage in the measurement system. The conversion includes; from one physical quantity to another, such as from resistance to voltage; or, from one form to another for the same physical quantity, such as from analog to digital.

Common Signal Conditioning Processes (cont'd)

- **Protection**: to prevent damage to the next stage due to excessive voltage or current, or polarity inversion of the signal.
- **Signal Manipulation**: to manipulate the sensor signal to obtain the suitable characteristic for further processing, such as the linearization of the sensor signal, and the conversion of the signal level to its root mean square (RMS) value.

Operational Amplifier (Op-Amp)

- Integrated circuit differential amplifier widely used in instrumentation circuits
- Basis of many signal conditioning modules
- Originated from analog computer circuits: performing operations such as addition and integration of signals; thus, named an operational amplifier
- Consists of two inputs and one output



Op-Amp

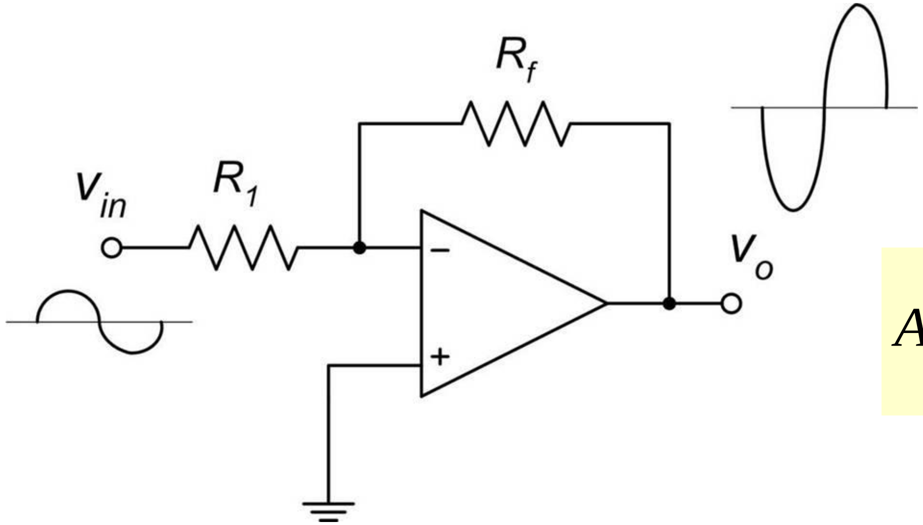
- An op-amp amplifies the voltage difference between the **non-inverting input** and the **inverting input**.
- **Feedback** refers to the return of part of the output to the input.
- **Open-loop** means operation without any feedback network.
- Op-amps are generally used with feedback.
- Passive components such as resistors and capacitors are usually used to form feedback networks for different op-amp circuit configuration.

OP-Amp Signal Conditioning Applications

- **Common op-amp circuits for signal conditioning** purposes:
  - Inverting Amplifier
  - Non-Inverting Amplifier
  - Voltage Follower
  - Summing Amplifier
  - Differential Amplifier
  - Instrumentation Amplifier
  - Logarithmic Amplifier
  - Integrator
  - Differentiator
  - Comparator

Inverting Amplifier

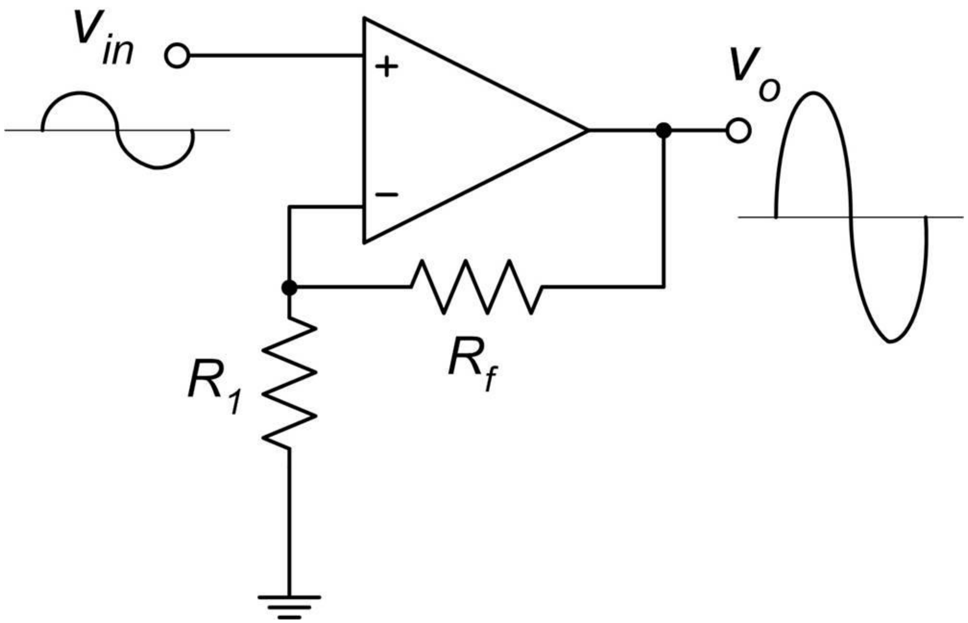
- Operates as a constant gain multiplier
- The applied signal is inverted.
- The feedback network consists of a single resistor, R_f (**feedback resistor**).
- R_1 is called an **input resistor**.



$$A_v = \frac{v_o}{v_{in}} = -\frac{R_f}{R_1}$$

Non-Inverting Amplifier

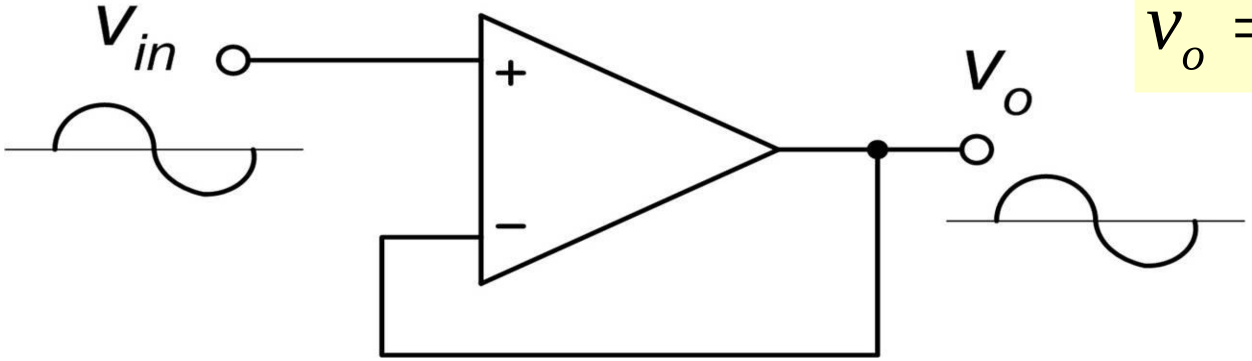
- Operates as a constant gain multiplier
- The applied signal is not inverted (the output is in phase with the input).
- The feedback network consists of a single resistor, R_f (**feedback resistor**).
- The input impedance of the circuit equals the input impedance of the op-amp.



$$A_V = \frac{v_o}{v_{in}} = 1 + \frac{R_f}{R_1}$$

Voltage Follower

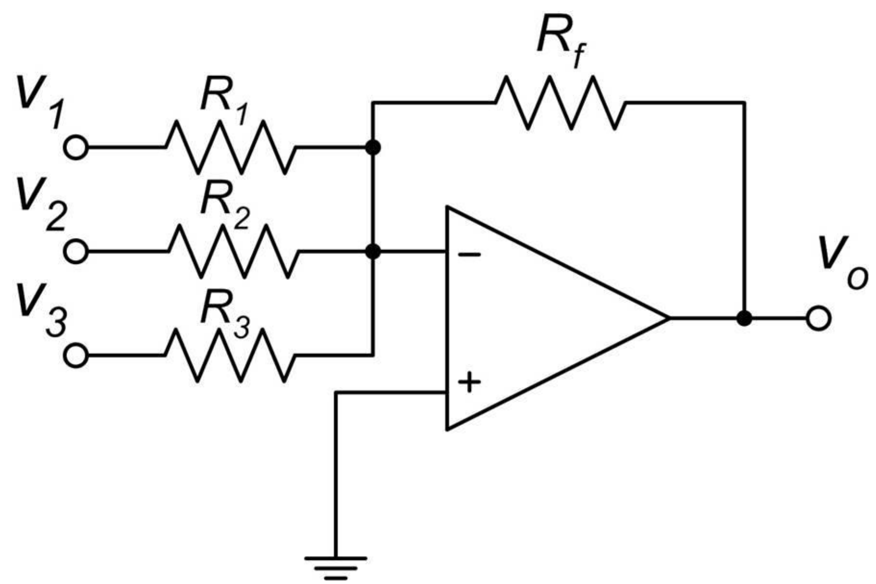
- Has unity voltage gain
- The output voltage follows the input voltage.
- The input impedance equals to the input impedance of the op-amp.
- Can be used as a buffer
- The very high input impedance and low output impedance enables the driving of current consuming loads, preventing loading effect.
- In effect, the voltage follower provides current gain.



$$v_o = v_{in}$$

Summing Amplifier

- The output voltage is proportional to the algebraic sum of its inputs, each multiplied by constant-gain factors.
- A summing amplifier with three inputs is shown; more inputs can be added by connecting the signal sources to the inverting input through input resistors.
- Application example: signal mixer.



$$v_o = -\left(\frac{R_f}{R_1} v_1 + \frac{R_f}{R_2} v_2 + \frac{R_f}{R_3} v_3 \right)$$

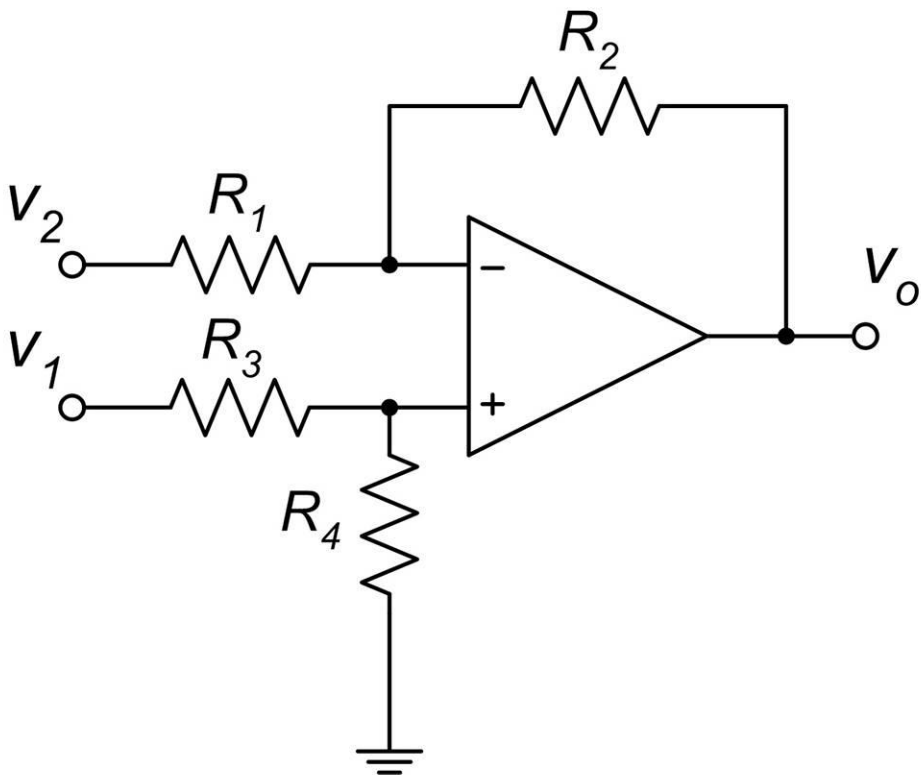
Differential Amplifier

- Input voltages are applied simultaneously to both the inverting and the noninverting inputs.
- Provides the subtraction of two signals.

$$v_o = \left(\frac{R_4}{R_1}\right)\left(\frac{R_1 + R_2}{R_3 + R_4}\right)v_1 - \frac{R_2}{R_1}v_2$$

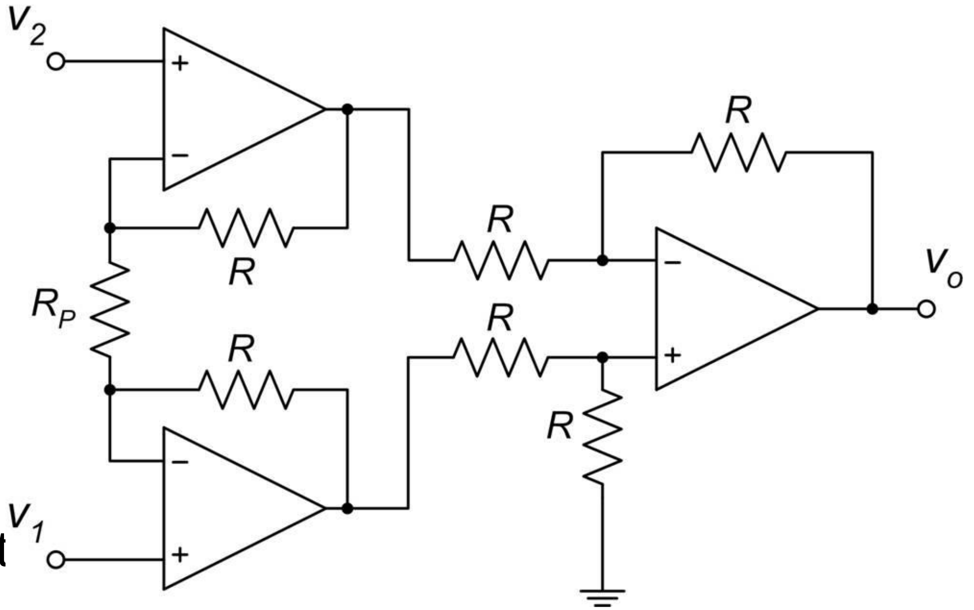
- If $\boldsymbol{R_1 = R_3}$ and $\boldsymbol{R_2 = R_4}$,

$$v_o = \frac{R_2}{R_1}\left(v_1 - v_2\right)$$



Instrumentation Amplifier

- **Instrumentation amplifier:** It amplifies the voltage difference between two inputs like a differential amplifier, but has a much higher **input impedance** and **CMRR**.
- Typically used as the first stage in **instrumentation systems** to amplify differential signals produced by **transducers**.
- Instrumentation amplifier IC that combines three op-amps and most resistors in a single package is available, with R_p as the only external component.
- The differential gain of the circuit is set by R_p.



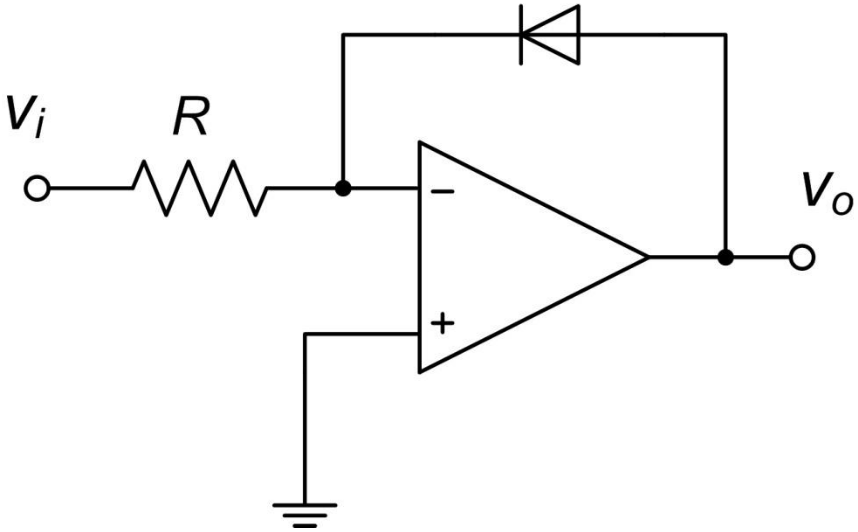
$$v_o = \left(1 + \frac{2R}{R_p}\right)(v_1 - v_2)$$

Logarithmic Amplifier

- The feedback network consists of a **diode**.
- Produces an output voltage proportional to the natural logarithm of the input voltage.
- $$v_o = -K \ln(\frac{v_i}{R})$$

where *K* is constant related to diode electrical properties.

- Can be used to linearize the sensor output with the exponential response.

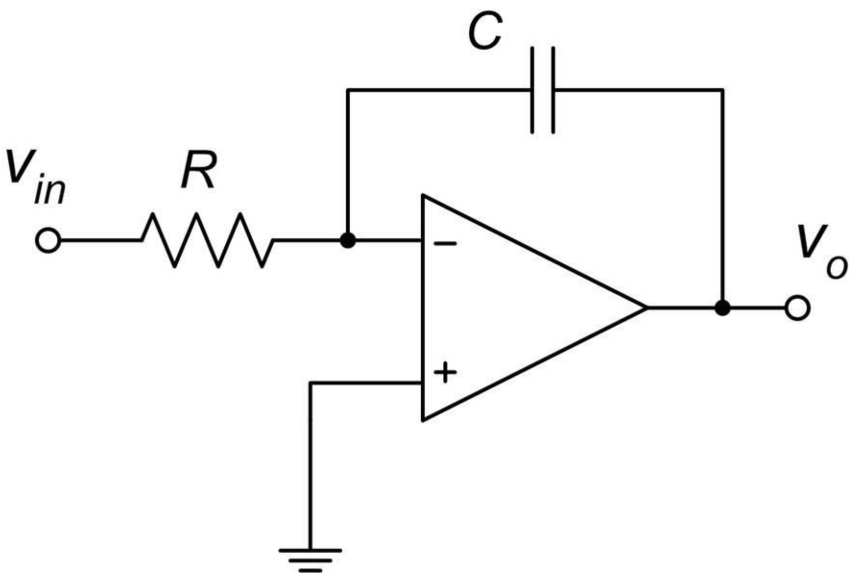


$$v_i = Ae^{at}, A \;\&\; a \text{ constants}$$

$$v_o = -K \ln(\frac{Ae^{at}}{R}) = -K[at + \ln(\frac{A}{R})]$$

Integrator

- The feedback network consists of a **capacitor**.
- Produces an output voltage proportional to the running time integral of the input voltage



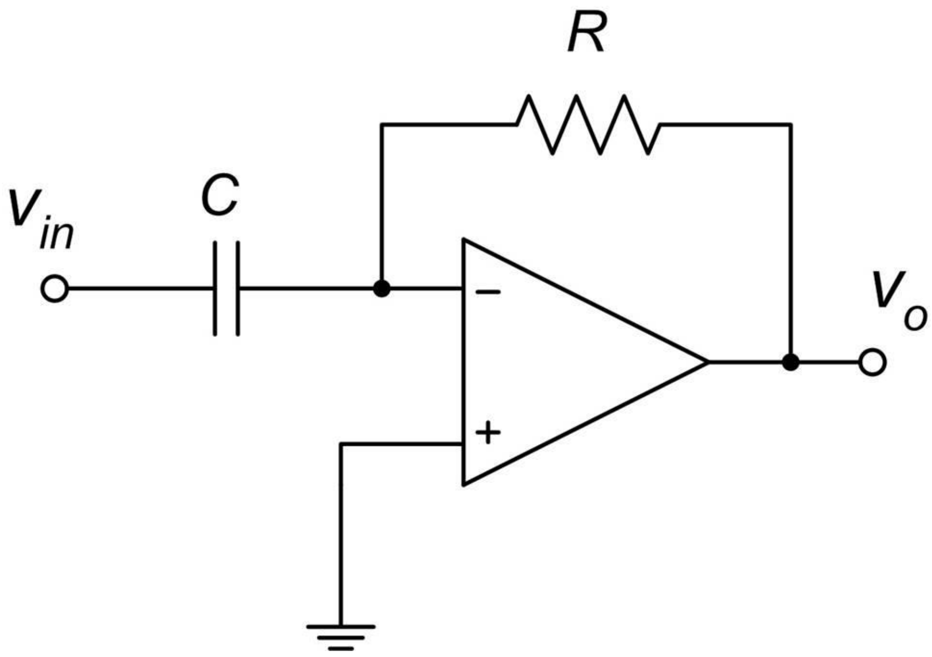
$$v_o(t) = -\frac{1}{RC}\int_0^{\tau} v_{in}(t)dt + v_o(0)$$

, where $v_o(0)$ is the initial value of v_o.

Differentiator

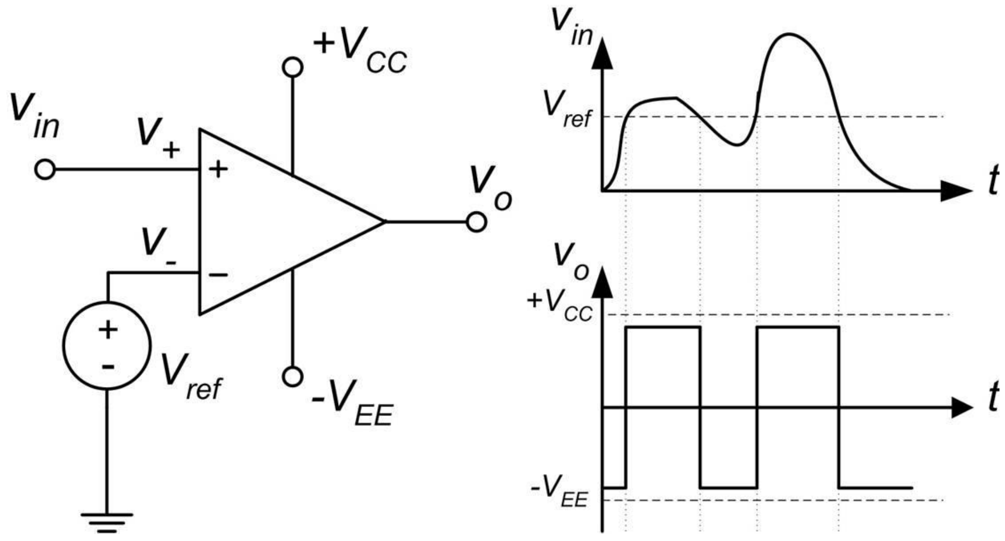
- Consists of an input capacitor and a feedback resistor
- Produces an output voltage proportional to the time derivative of the input voltage

$$v_o(t) = -\frac{1}{RC}\frac{dv_{in}}{dt}$$



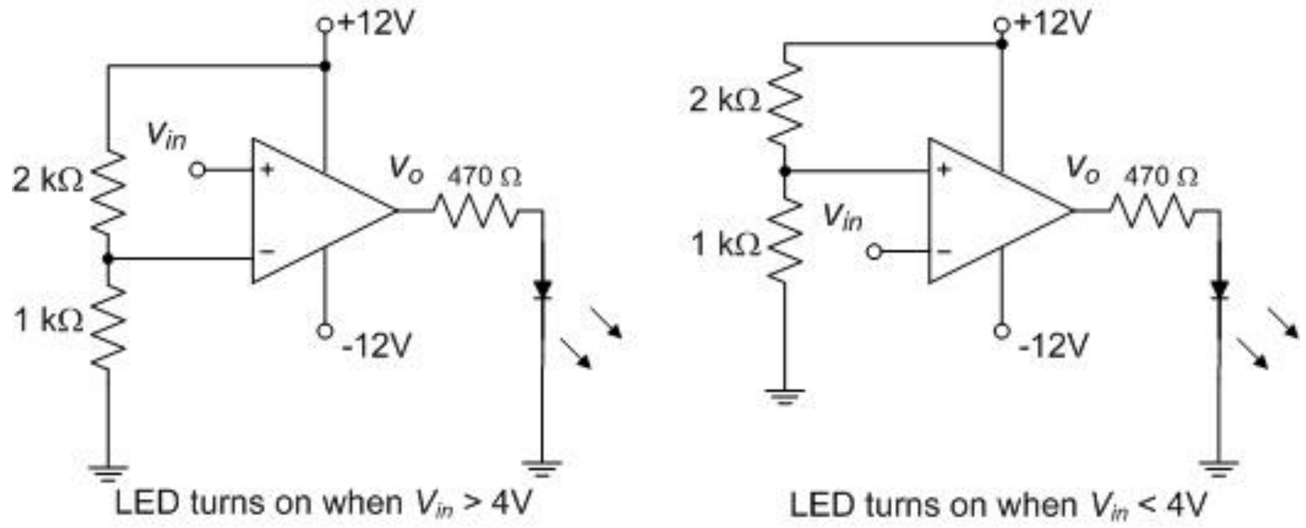
Comparator

- Accepts the input of linear voltages and provides a **discrete output** indicating when one input is **less** or **greater** than the other.
- No feedback network; the voltage gain equals the very high open-loop gain.
- The output clips near positive or negative supply voltage ($+V_{CC}$ or $-V_{EE}$) whenever the voltage difference at the inputs is positive or negative respectively.



Comparator (cont'd)

- When $V_+ > V_-$, V_o clips to the positive saturation voltage, near $+V_{CC}$.
- When $V_+ < V_-$, V_o clips to the negative saturation voltage, near $-V_{EE}$.
- An input voltage, V_i is compared against a reference voltage, V_f.
- The V_i and V_f can be connected to the inverting or noninverting inputs, producing opposite results.
- Resistor voltage divider network can be used to provide V_f.

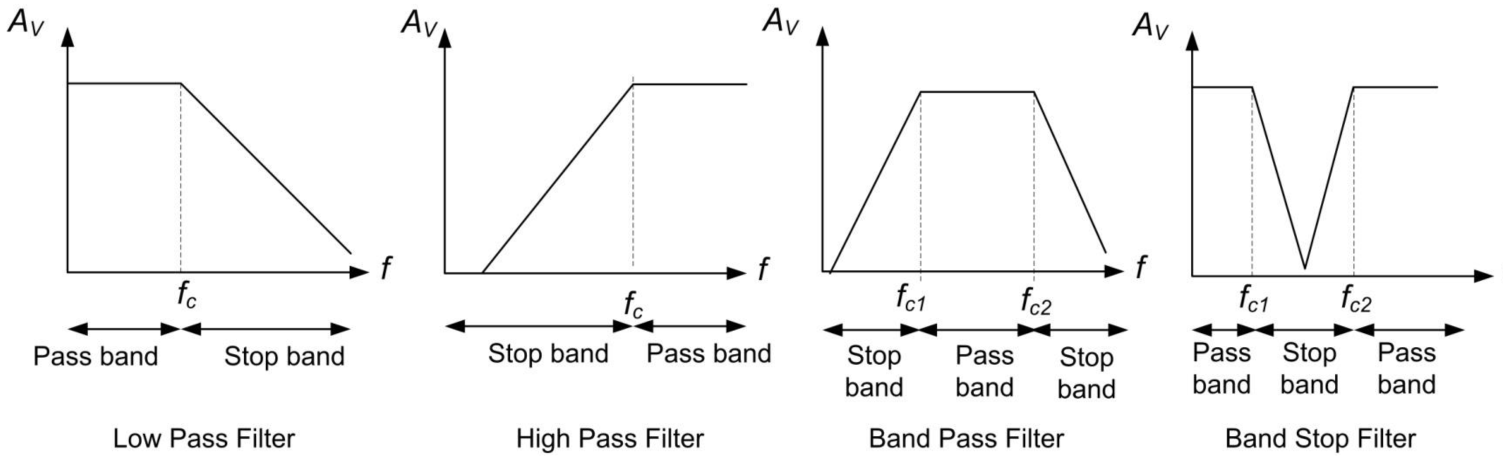


Analog Filters

- **Filter circuit:** frequency-selective circuit that passes a specified band of frequencies and attenuates signals of frequencies outside this band.
- The filtering process can be implemented as an analog circuit (analog filter) or a program carried out by a microprocessor (digital filter).
- Analog filter circuits can be categorized as follows:
  - **Passive filters:** Filters employing only **passive elements** (R, L, and C).
  - **Active filters:** Filters employing active components such as **op-amps** in addition to resistors and capacitors.
- Filter circuits can be further categorized according to **type** (the way the filter circuit responses to different frequency components), **class** (the shape of the frequency and phase response curves), or **order** (the order of the filter transfer function equation) of filters.

Analog Filters (cont'd)

- Common filter types:
  - Low Pass: passing frequency components below the cut-off frequency
  - High Pass: passing frequency components above the cut-off frequency
  - Band Pass: passing frequency components between the two cut-off frequencies
  - Band Stop: rejecting frequency components between the two cut-off frequencies

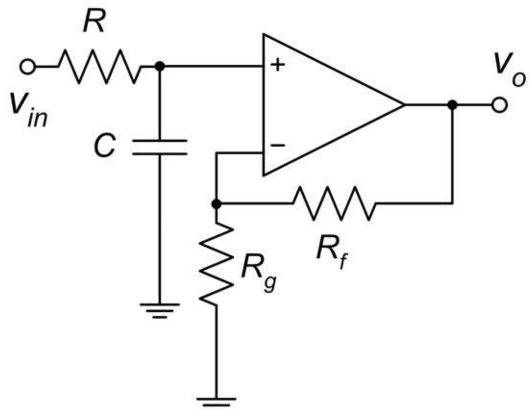


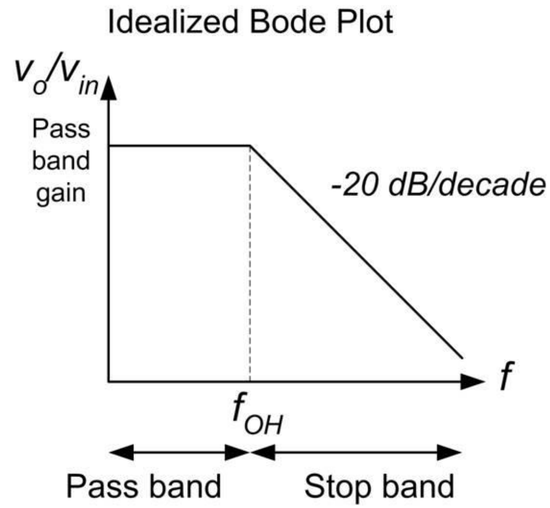
Analog Filters (cont'd)

- Common filter classes:
  - Butterworth
  - Chebyshev
  - Bessel
  - Elliptic
- The 1st order and 2nd order active filters are used as the building blocks for higher order active filters.
- A building block for an active filter consists of two major components: **a frequency-selective RC network** and **an op-amp.**

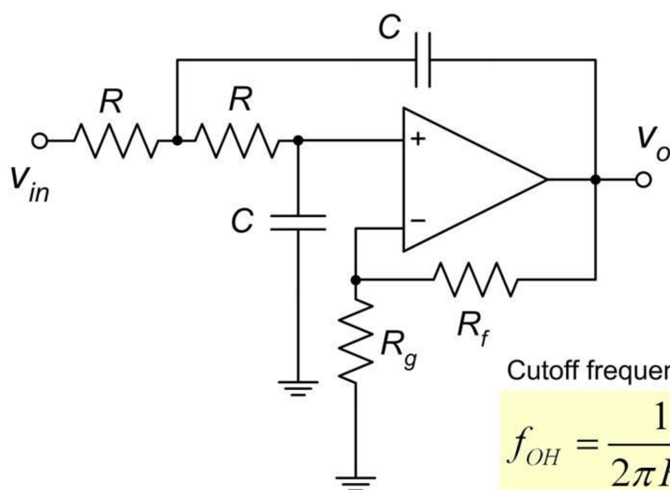
Analog Filter Examples

- 1st order active low pass filter



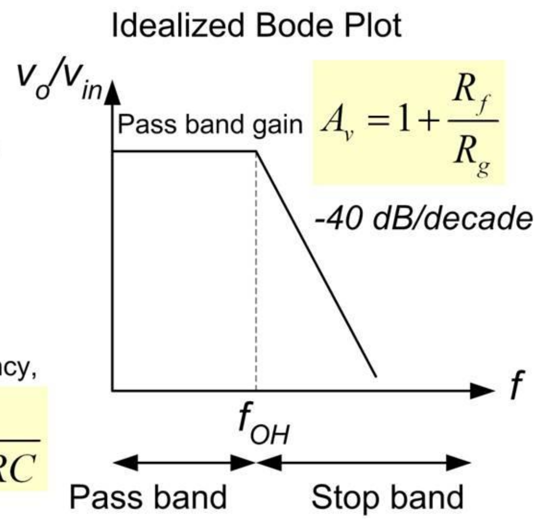


- 2nd order active low pass filter



Cutoff frequency,

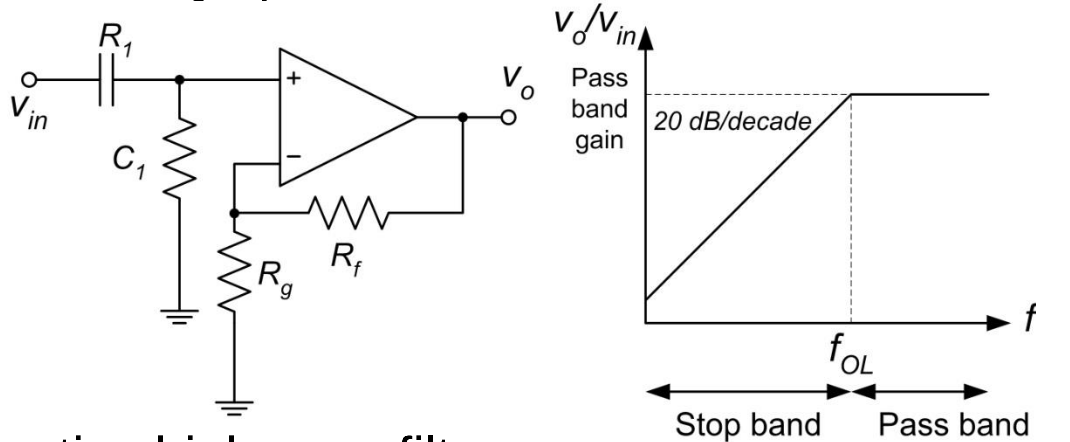
$$f_{OH} = \frac{1}{2\pi RC}$$



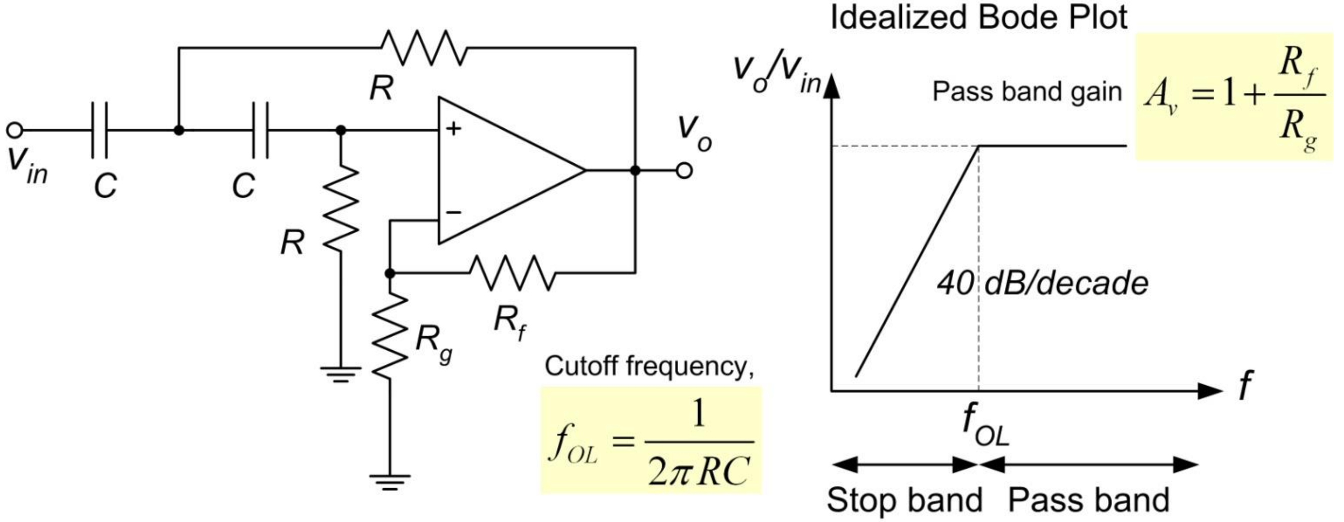
$$A_v = 1 + \frac{R_f}{R_g}$$

Analog Filter Examples (cont'd)

- 1st order active high pass filter



- 2nd order active high pass filter

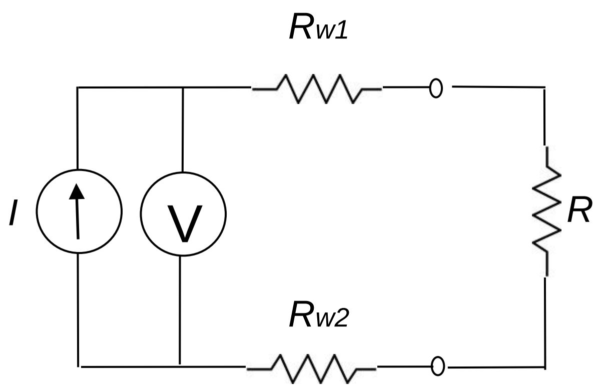


Signal Conversion

- Many sensors convert change in some physical quantities into electrical quantities such as resistance and reactance (capacitance or inductance).
- Most electronic measuring equipments detect change in voltage, requiring the sensor output to be converted into voltage.
- Signal conditioning circuits are utilized to convert resistive and reactive sensor output into voltage.

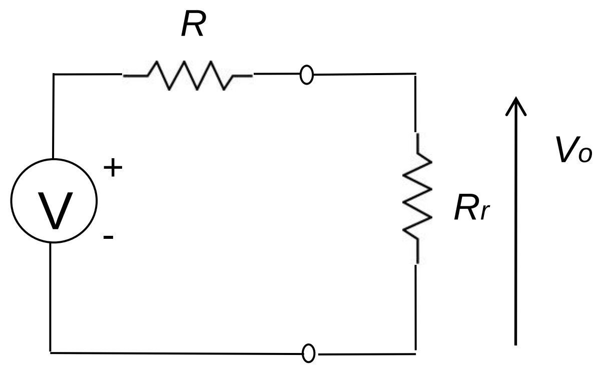
Resistive Sensor Signal Conditioning

- The simplest signal conditioning for resistive sensors involves connecting the sensor to a constant current source and measuring the voltage drop across the sensor.



- The voltage drop across the sensor *R* is proportional to the resistance.
- Lead resistances R_{W1} and R_{W2} can be ignored for high *R* values.

Resistive Sensor Signal Conditioning (cont'd)

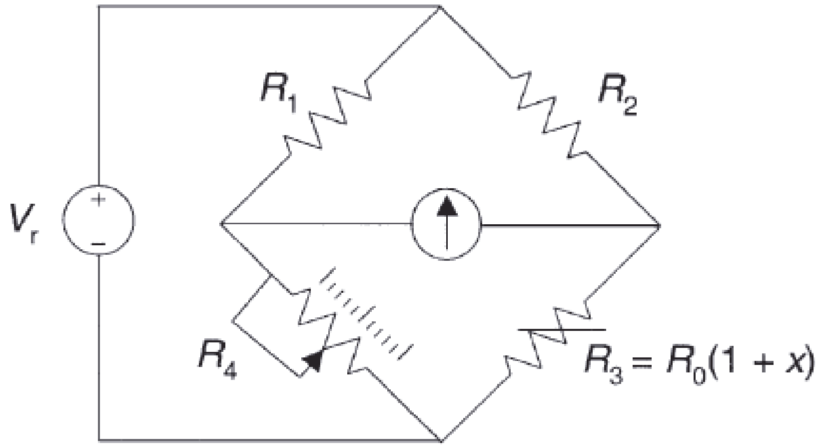


$$V_o = \frac{R_r}{R + R_r} \times V_r$$

- Voltage divider circuits are commonly employed for high resistance measurement.
- Sensor *R* forms a voltage divider with resistor R_r.
- The output voltage is inversely proportional to resistance or *R*, making it suitable to linearize the sensor output which is inversely proportional to the measured quantity.

Resistive Sensor Signal Conditioning (cont'd)

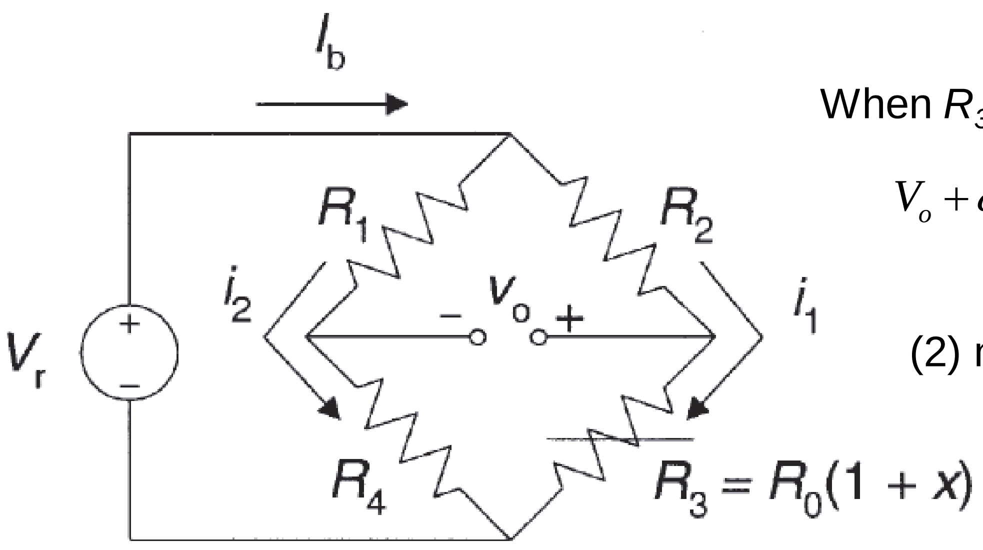
- The Wheatstone bridge is also used to convert change in resistance to change in voltage.
- The resistive sensor and three other resistors form a bridge circuit connecting to an excitation voltage source.
- Works in balance mode and deflection mode



Resistive Sensor Signal Conditioning (cont'd)

- In deflection mode, the Wheatstone bridge is not balanced by adjusting a variable resistor.
- The resistive sensor is connected as R_3, while R_1, R_2,and R_4 are fixed resistors.
- The voltage across the bridge is the output for the circuit.

$$V_o = V_r\left(\frac{R_3}{R_2+R_3} - \frac{R_4}{R_1+R_4}\right) \quad (1)$$



[2]

When R_3 increases to $R_3 + \delta R$, V_o changes to $V_o + \delta V$

$$V_o + \delta V = V_r\left(\frac{R_3+\delta R}{R_2+R_3+\delta R} - \frac{R_4}{R_1+R_4}\right) \quad (2)$$

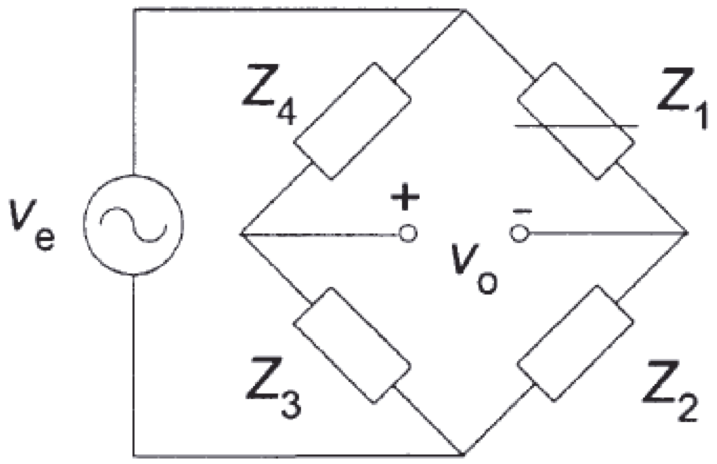
(2) minus (1) $$\delta V = V_r\left(\frac{R_3+\delta R}{R_2+R_3+\delta R} - \frac{R_3}{R_2+R_3}\right)$$

When $R_3 \gg \delta R$, δV is proportional to δR

$$\delta V \approx V_r\left(\frac{\delta R}{R_2+R_3}\right)$$

Reactive Sensor Signal Conditioning

- An alternating current (AC) voltage excitation source is needed for a sensor with reactive (capacitive or inductive) output to produce output in voltage.
- AC bridge circuits are used to convert varying reactance into AC voltage with varying amplitude.



$$V_o = V_e\left(\frac{Z_4}{Z_3 + Z_4} - \frac{Z_1}{Z_1 + Z_2}\right)$$

For a capacitive sensor with capacitance *C*, excited by an AC source with frequency *f* , the magnitude of the sensor impedance

$$|Z| = |X_C| = \frac{1}{2\pi fC}$$

For an inductive sensor with inductance *L*, excited by an AC source with frequency *f*, the magnitude of the sensor impedance

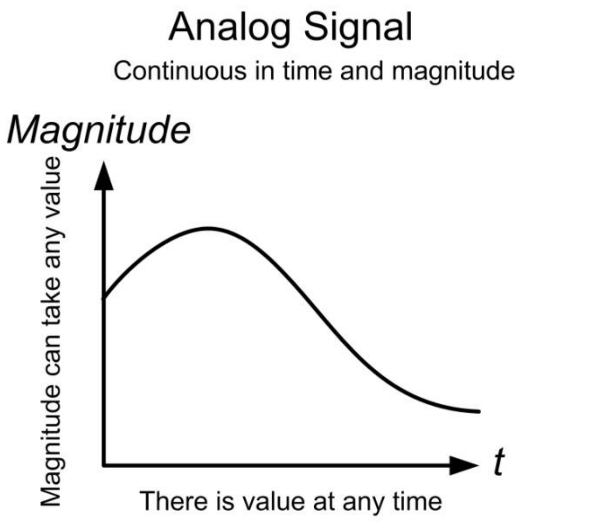
$$|Z| = |X_L| = 2\pi fL$$

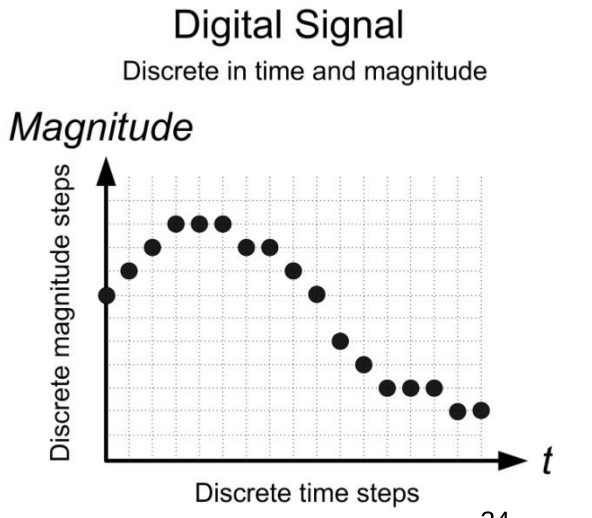
Analog to Digital Conversion

- Digital data processing and recording systems such as computers require the sensor signal to be available in binary form.
- Analog to digital conversion turns analog signals into binary words corresponding to the signal values.
- Analog to digital converter (ADC) is a circuit that converts analog voltage into digital values; usually available as an integrated circuit.
- ADC operation can be divided into two parts:
  - Sampling
  - Quantization

Analog to Digital Conversion (cont'd)

- An analog signal is continuous, both in time and in magnitude – the signal can have a magnitude of any value, at any time.
- A digital signal is discrete, both in time and in magnitude – the signal can only have a magnitude of certain predefined values, at predefined time intervals.
- This is because the digital signal is represented as a stream of binary values of a finite word length – exists in steps of time and value.

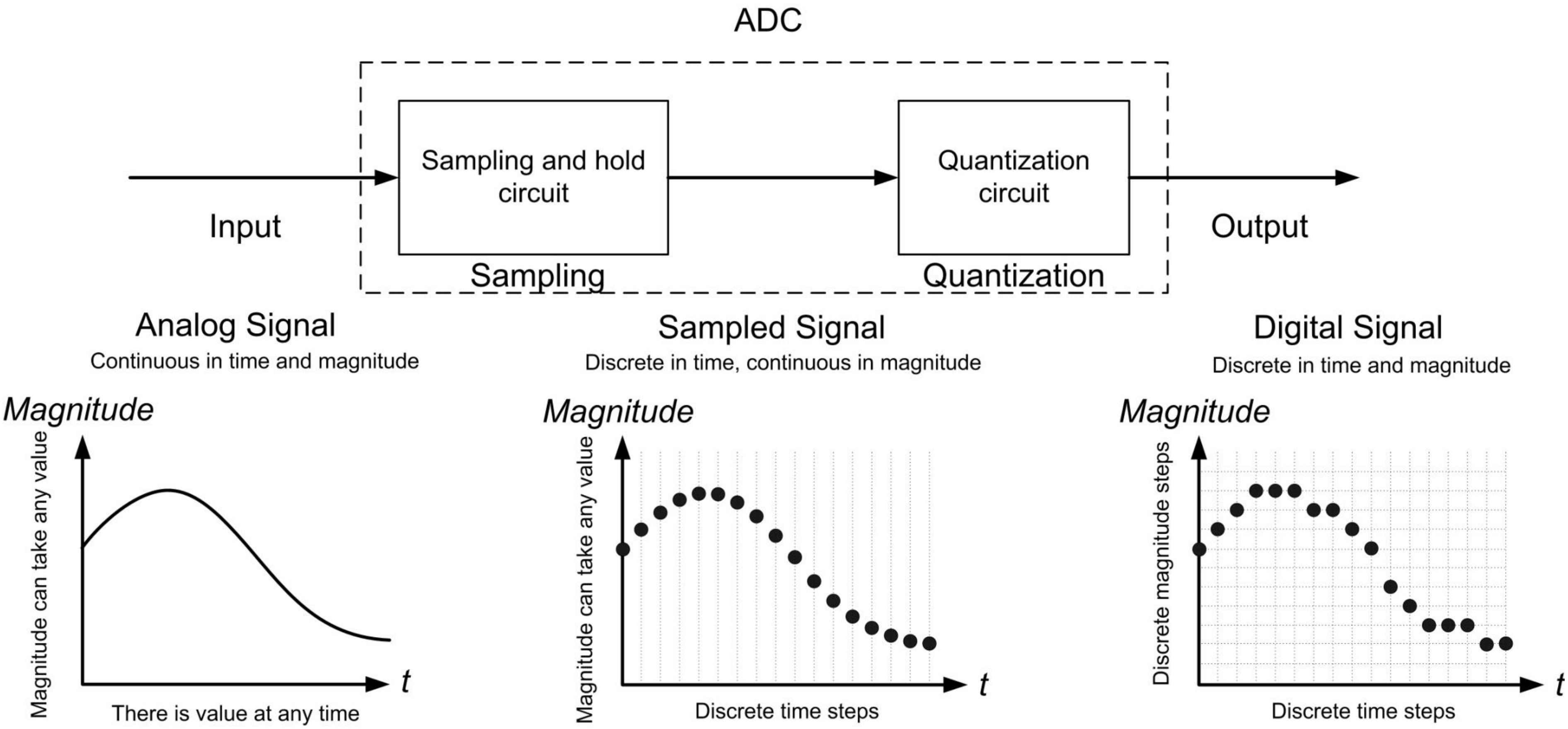




Analog to Digital Conversion (cont'd)

- Sampling is done by a sample and hold circuit, producing values at a predefined interval (sampling interval) for digitization.
- Quantization is a process where the analog values at discrete time intervals are converted into discrete binary values.
- During quantization, ADC uses an integer value from a predetermined, finite list of values to represent each analog sample.
- Each integer value in the list represents a fraction of the full scale voltage range of the ADC.

Analog to Digital Conversion Process



Sampling Frequency

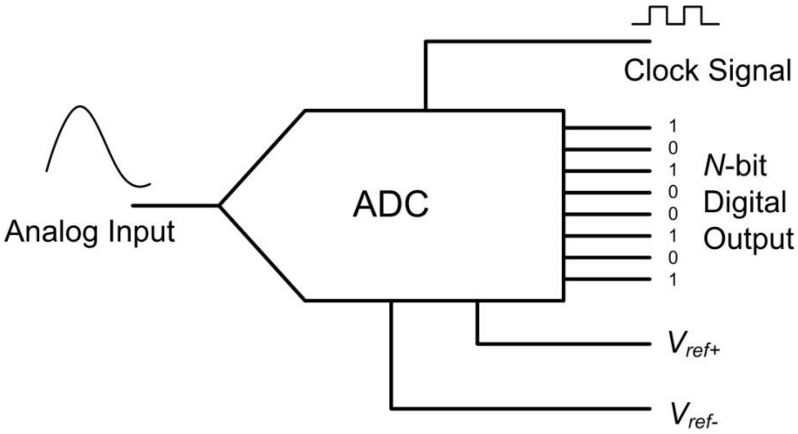
- According to the Shannon-Nyquist sampling theorem, the sampling rate must be at least twice that of the highest frequency in the analog signal in order to accurately reproduce the signal in the digital domain:

sampling rate/frequency, $f_s \geq 2f_{max}$

- Nyquist frequency: the frequency twice of the maximum signal frequency.
- When the sampling rate is lower than the Nyquist frequency, **aliasing** occurs.

ADC Resolution

- Resolution of an ADC refers to the smallest change in voltage the ADC can detect, which is the voltage represented by one least significant bit (LSB) in the converted value.
- ADC generates a binary output which is a fraction of its full scale voltage range, V_{FSR}.
- The full scale voltage range depends on the reference voltage connected to the ADC.



- For bipolar operation, there are two reference voltage pins on the ADC, V_{ref+} and V_{ref-} : $V_{FSR} = V_{ref+} - V_{ref-}$.
- For single ended operation, there is usually one reference voltage pin on the ADC, V_{ref} while V_{ref-} is grounded internally: $V_{FSR} = V_{ref}$.
- A N-bit ADC can produce 2^N possible output combinations, with $2^N - 1$ intervals between two successive values.
- Resolution of a N-bit ADC, $Q = V_{FSR}/(2^N - 1)$
- To interpret the converted binary value,

$$\text{Converted Voltage} = \frac{V_{FSR}}{2^N - 1} \times (\text{ADC digital output value})$$