CSE2050 Sensors and Actuators

Module 1

Fundamentals of Sensing, Sensors and Actuators

Course Objectives

To understand/Study

- the big picture of sensors and actuators.
- the fundamentals of sensor and actuator working principles.
- the interfacing of analog sensors, digital sensors, MEMS sensors and actuators.
- the fundamentals of conversion of sensor data.

Syllabus

Module:1	**Fundamentals of Sensing, Sensors and Actuators**	**2 hours**
Sensing modalities- mechanical sensors, optical sensors, semiconductor sensors, electrochemical sensors, biosensors and application domains. Signal conditioning - voltage divider, amplifiers, filters, analog-to-digital conversion, supply voltage. Digital sensors - buttons and switches, I2C devices, SPI devices, RS-232 and other sensors. Actuators - Switches and Motors.		
Module:2	**Performance characteristics of sensors and actuators**	**5 hours**
Input and output characteristics. Range, span, input and output full scale, resolution, and dynamic range - resolution of a system, resolution of analog and digital sensors. 10/12/16bit Analog to Digital conversion of analog output of sensors. Accuracy, errors, and repeatability. Frequency response, response time, and bandwidth.		
Module:3	**Temperature sensors and thermal actuators**	**4 hours**
Thermoresistive sensors - Resistance temperature detectors, Silicon resistive sensors, Thermistors. Analog to Digital conversion of temperature. Interfacing of temperature sensor and actuators with Raspberry pi, Arduino or other microcontrollers.		
Module:4	**Optical sensors and actuators**	**4 hours**
Photoelectric sensors. Thermal-based optical sensors - passive IR sensors, thermopile PIR, pyroelectric sensors, bolometers, active far infrared (AFIR) sensors. Optical actuators. Analog to Digital conversion of optical sensor output. Interfacing of optical sensors and actuators with Raspberry pi, Arduino or other microcontrollers.		
Module:5	**Electric and magnetic sensors and actuators**	**5 hours**
Magnetohydrodynamic (MHD) sensors and MHD actuators. Magnetometers - coil magnetometer, fluxgate magnetometer. Magnetic actuators - motors as actuators, magnetic solenoid actuators and magnetic valves. Voltage and current sensors - voltage sensing, current sensing and resistance sensing. Analog to Digital conversion of electric and magnetic sensor outputs. Interfacing of electric and magnetic sensors and actuators with Raspberry pi, Arduino or another microcontroller.		

Module:6	**Mechanical sensors and actuators**	**4 hours**
Force sensors, Accelerometers, Pressure sensors, Velocity sensing and Inertial sensors: gyroscopes - Analog to Digital conversion - Interfacing of sensors and actuators with Raspberry pi, Arduino or other microcontroller.		
Module:7	**MEMS, smart sensors and actuators**	**4 hours**
MEMS sensors - pressure sensors, mass air flow sensors, inertial sensors, angular rate sensors. MEMS actuators - thermal and piezoelectric actuation, electrostatic actuation. Interfacing of MEMS sensors and activators with Raspberry pi, Arduino or another microcontroller using I2C, SPI and other protocols. Smart sensors and actuators - wireless sensors and actuators.		
Module:8	**Contemporary issues**	**2 hours**
	Total Lecture hours:	**30 hours**

Text Book(s)

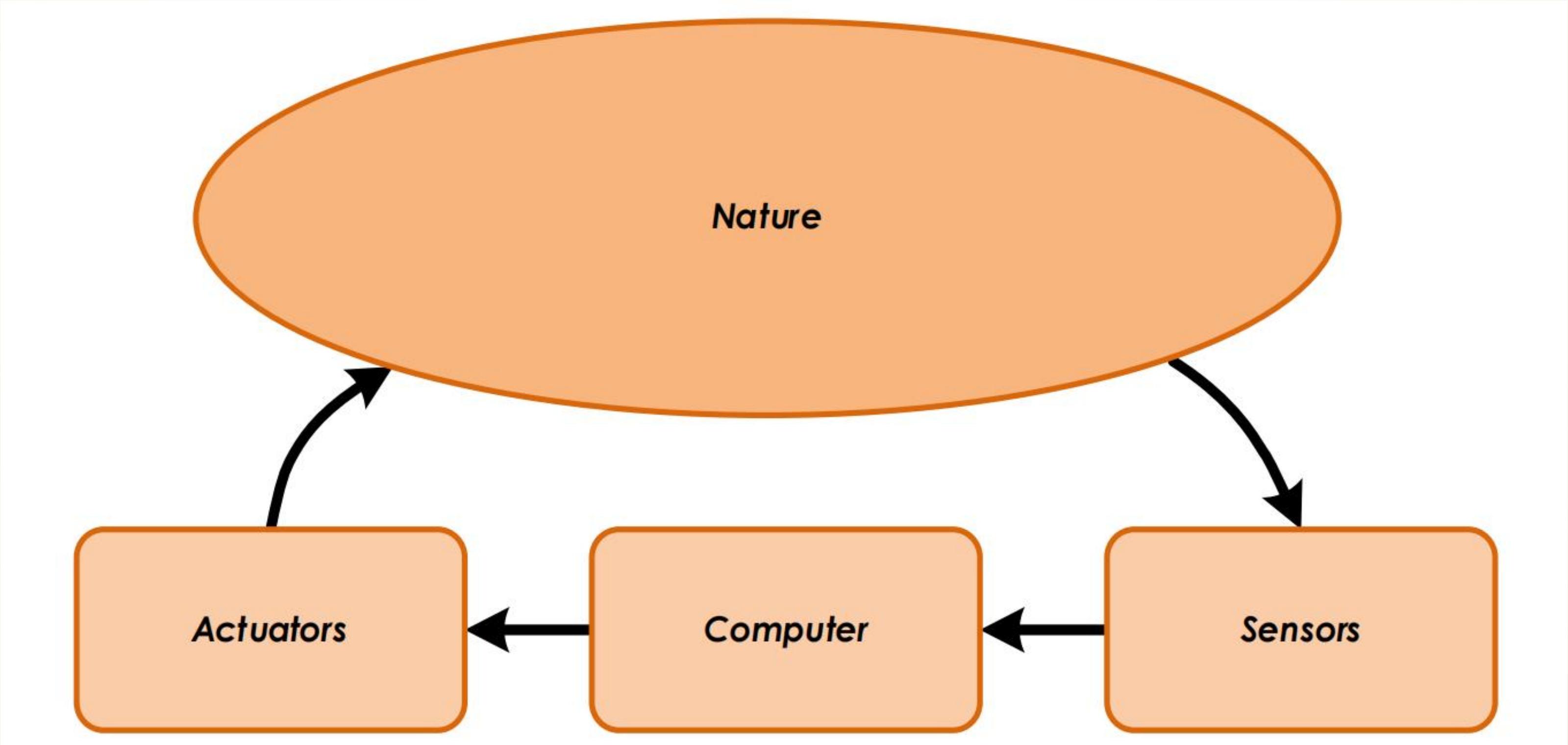
1. Nathan Ida , Sensors, Actuators, and Their Interfaces A multidisciplinary introduction, 2nd Edition, 2020.

Reference Books

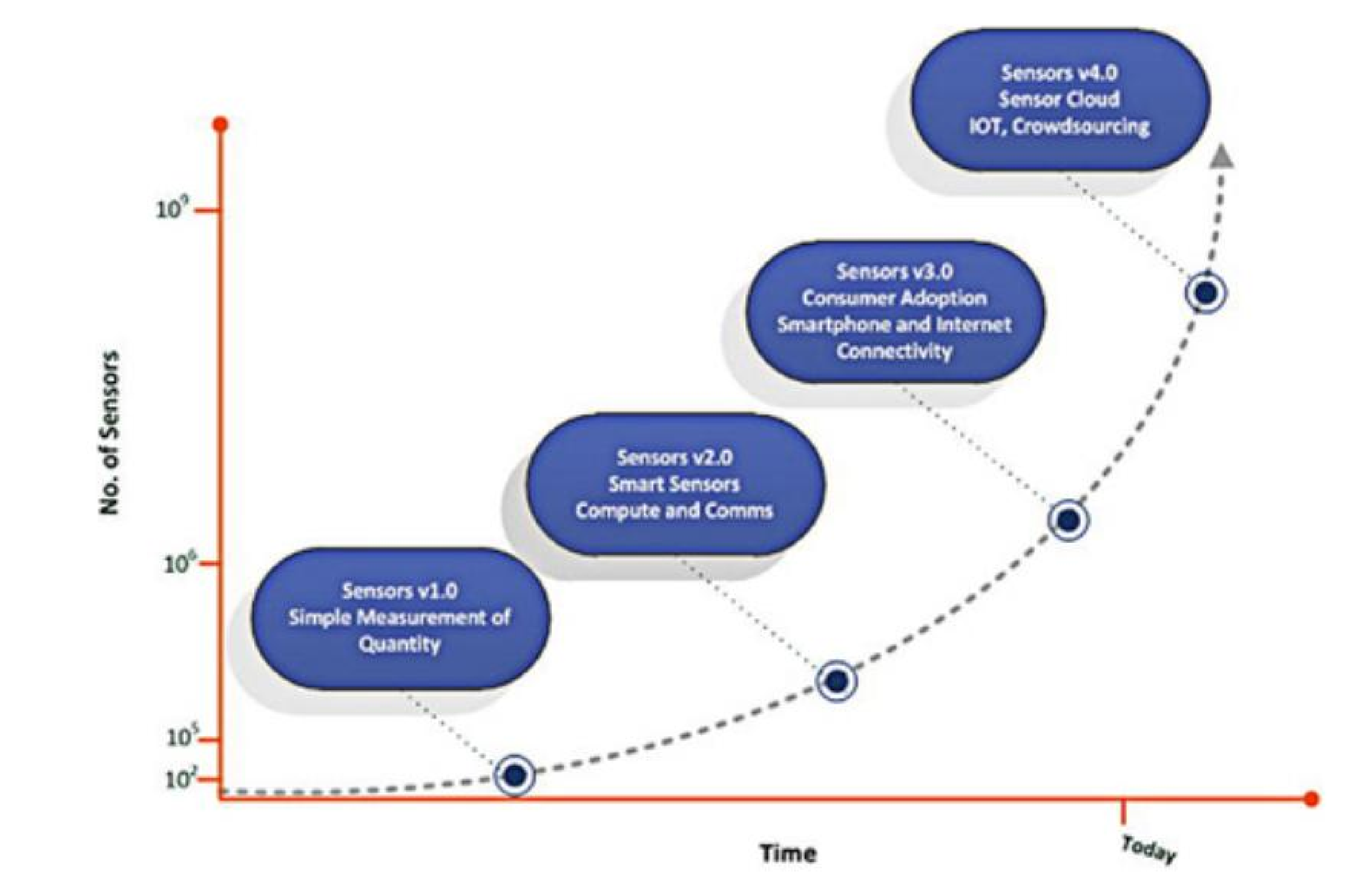
1. Michael J. McGrath, Cliodhna Ni Scanaill, Sensor Technologies: Healthcare, Wellness, and Environmental Applications, 2014.
2. Volker Ziemann, A Hands-On Course in Sensors Using the Arduino and Raspberry Pi, 2018.
3. Francisco André Corrêa Alegria, Sensors and Actuators, 2021.
4. Wolfram Donat, Make a Raspberry Pi–Controlled Robot, 2015.

Introduction

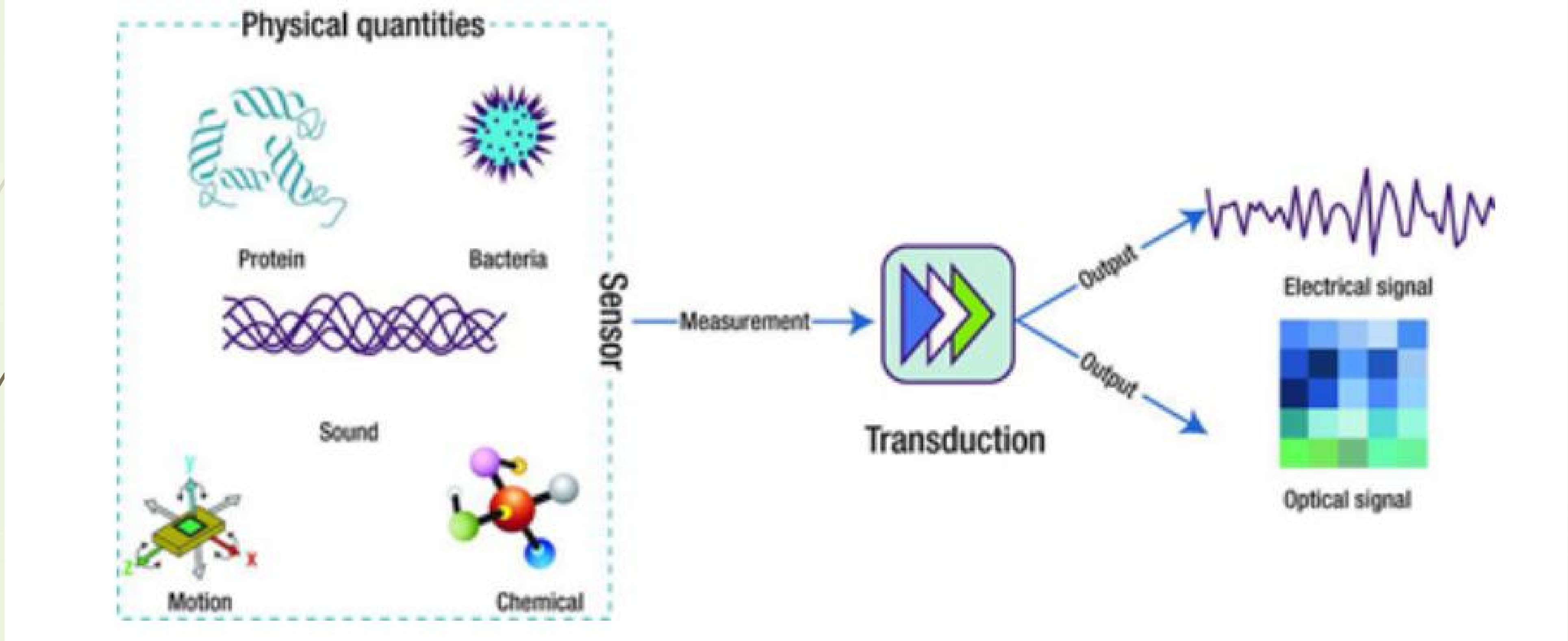
- **Sensors and actuators** are two **critical components** of every **closed loop control system**



Introduction



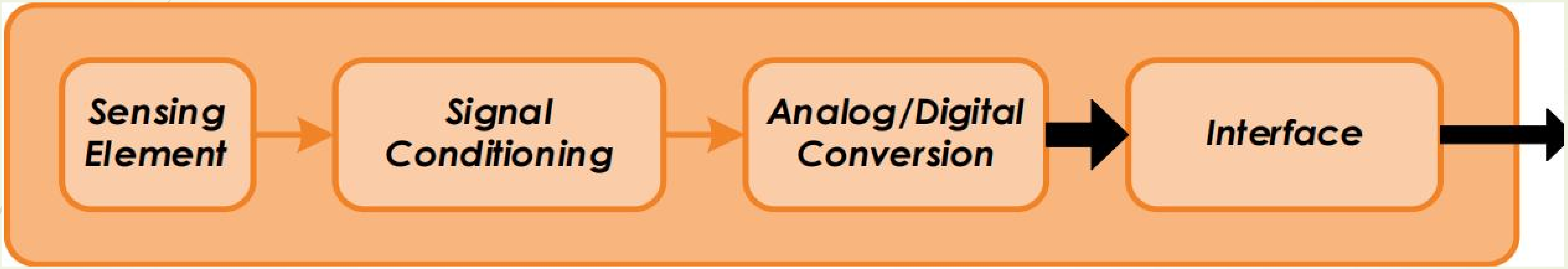
Introduction



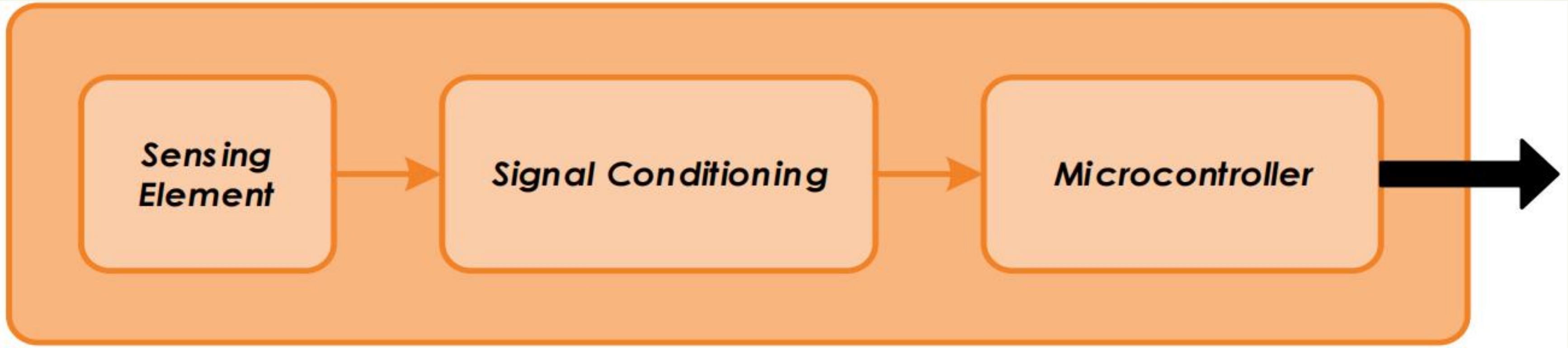
Introduction

- A transducer is a device that converts one form of energy into another
- Both sensors and actuators are transducers
- Sensor is a device that when exposed to a physical phenomenon (temperature, displacement, force, etc.) produces a proportional output electrical signal.
- An actuator is a device that receives a command, usually in the form of an electrical signal, and makes a change in Nature, producing, for example, a force, a sound, heat, etc.

Introduction



Architecture of an integrated sensor



Smart Sensor

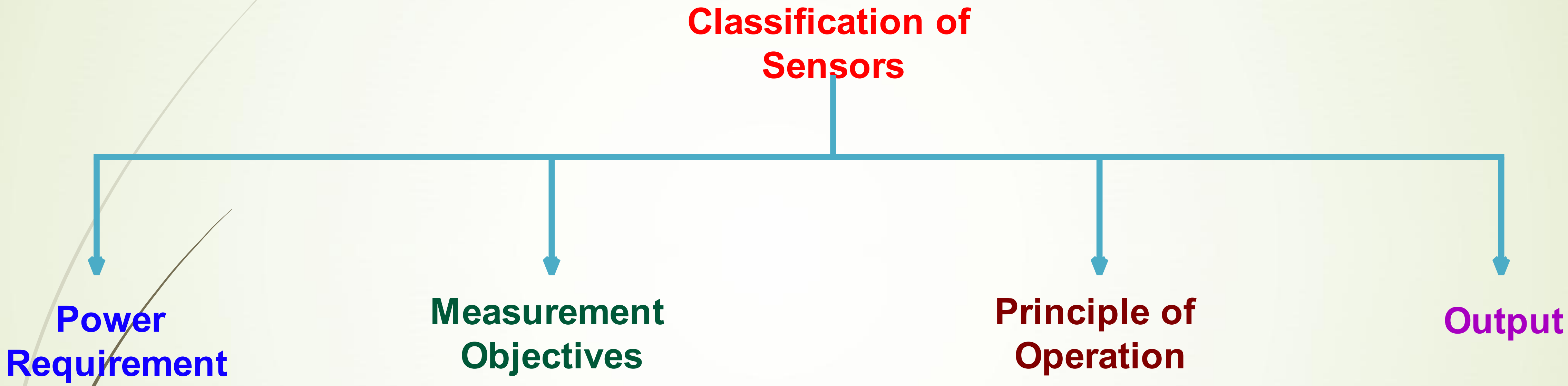
Key Sensing Modalities

- Sensors which measure same form of energy and process it in similar ways
- **"Modality"** refers to the **raw input** used by the sensors

Different modalities:

- Sound
- Pressure
- Temperature
- Light
  - Visible light
  - infrared light
  - X-rays, etc.,

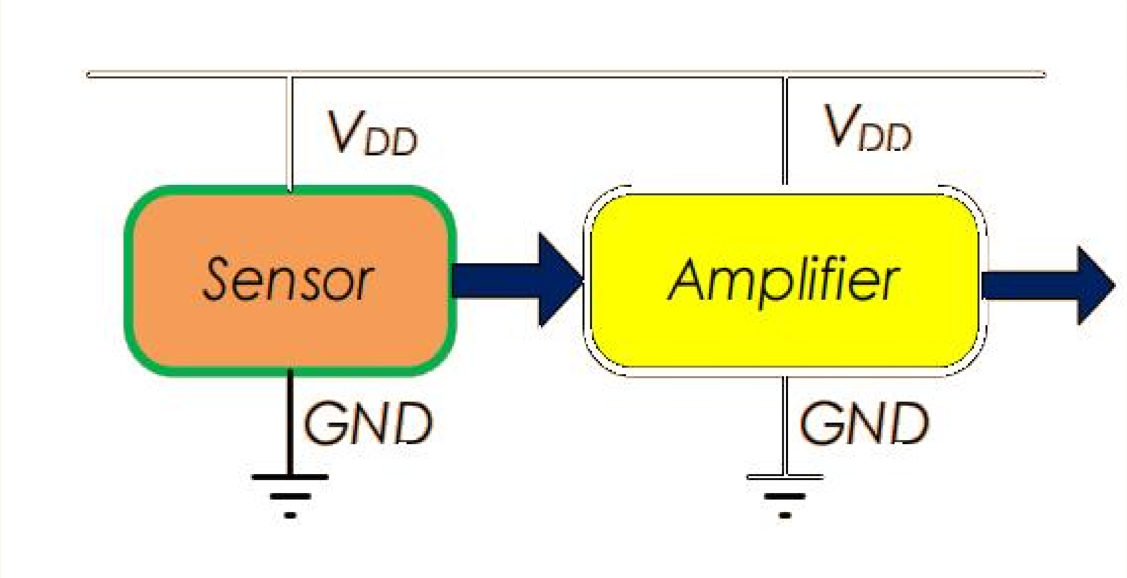
Classification of Sensors



Classification of Sensors

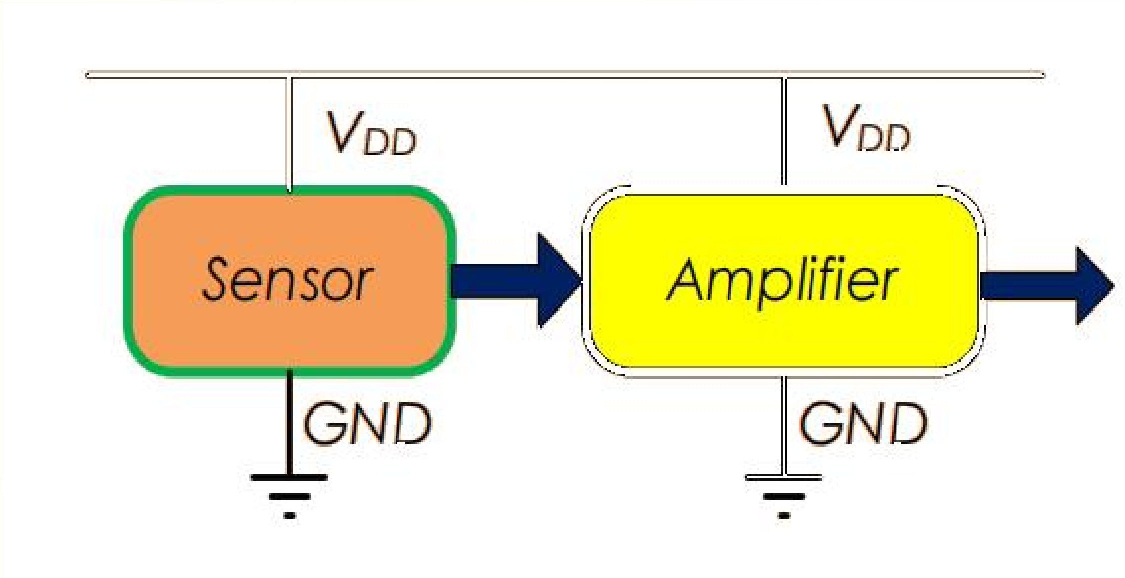
- **Classification of Sensors**
  - **Power Requirement**
    - Active Sensor
    - Passive Sensor
  - **Measurement Objectives**
    - Temperature Sensor
    - Pressure Sensor
    - Level Sensor
    - Flow Sensor, etc.,
  - **Principle of Operation**
    - Resistive Sensor
    - Capacitive Sensor
    - Inductive Sensor
    - Ultrasonic Sensor
  - **Output**
    - Analog Sensor
    - Digital Sensor

Active Sensors and Passive Sensors

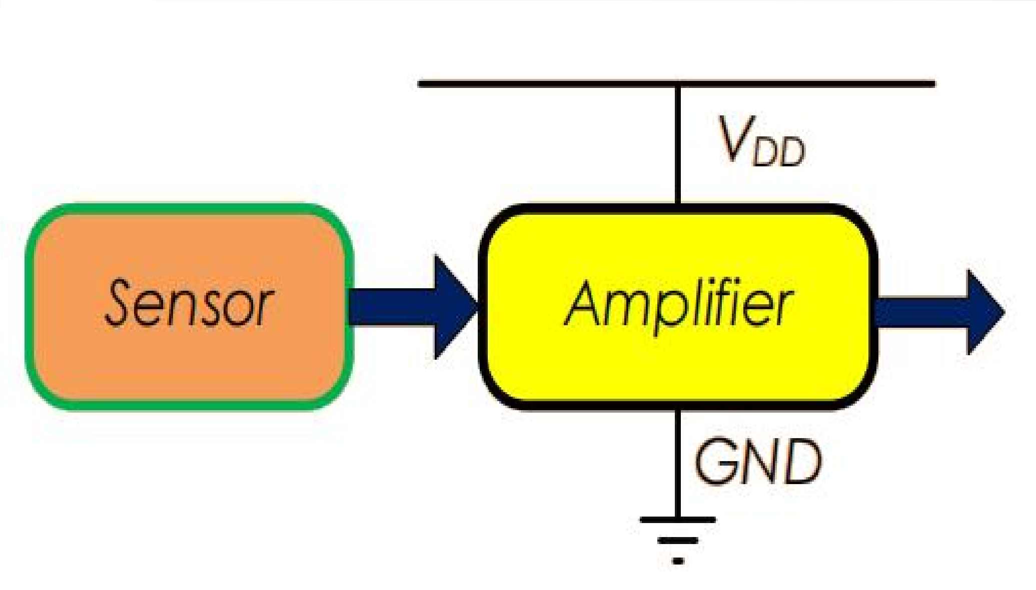


Active Sensors

Active Sensors and Passive Sensors

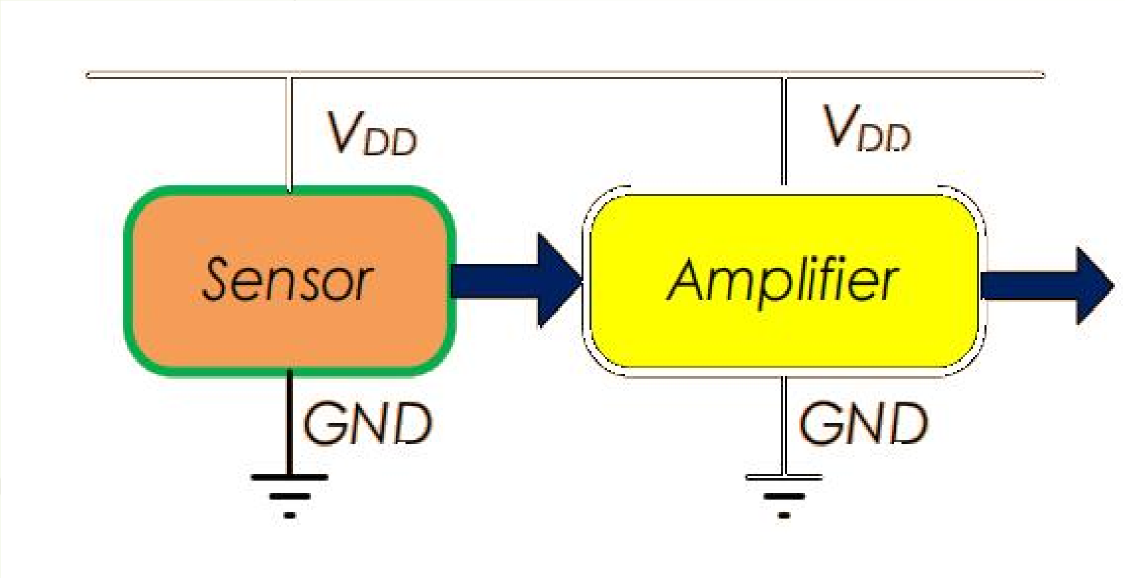


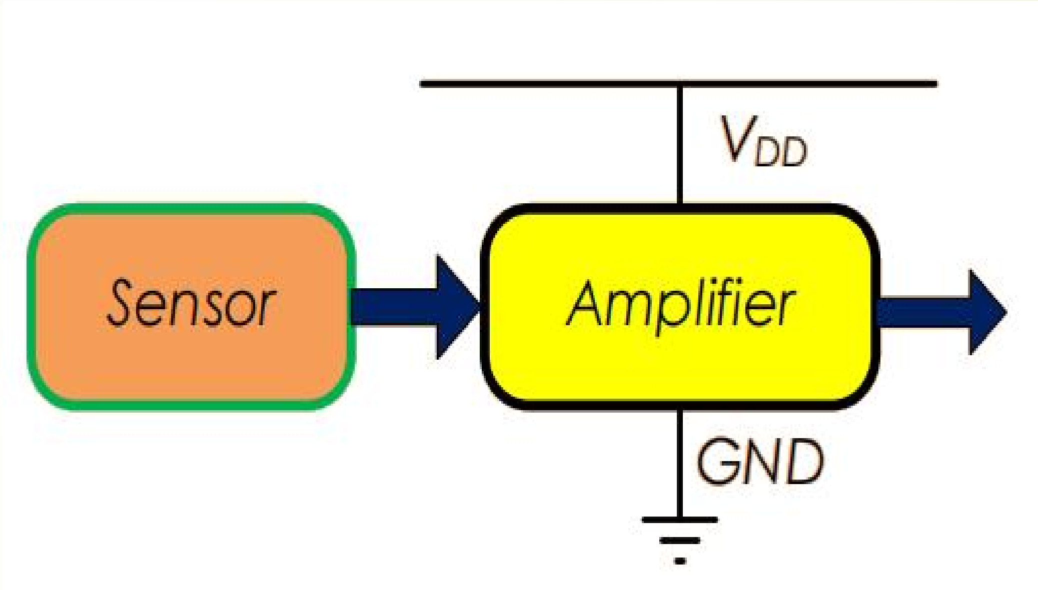
Active Sensors



Passive Sensors

Active Sensors and Passive Sensors





Active Sensors

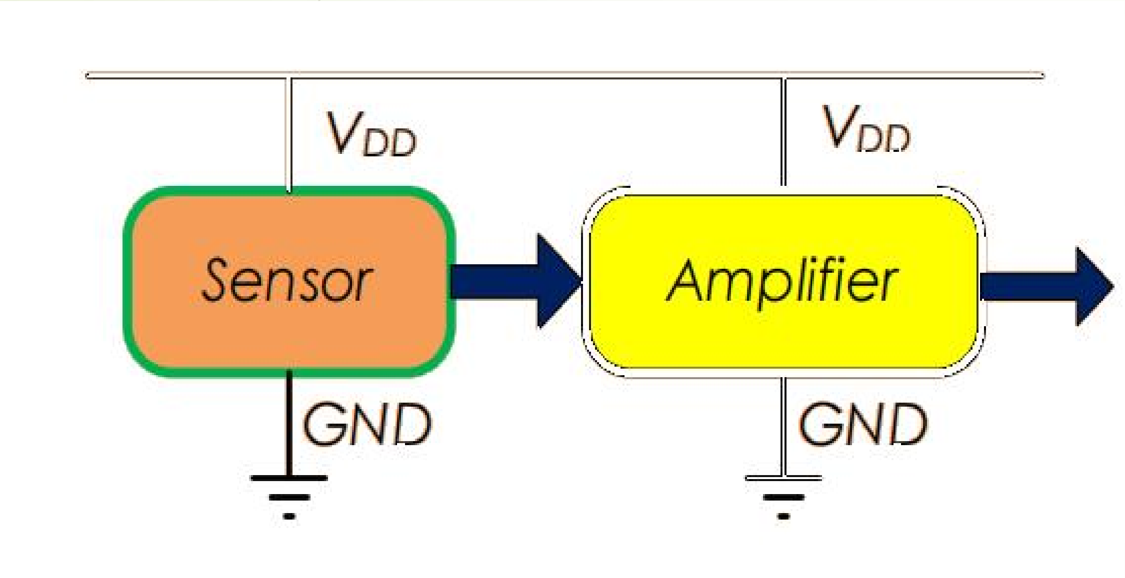
Passive Sensors

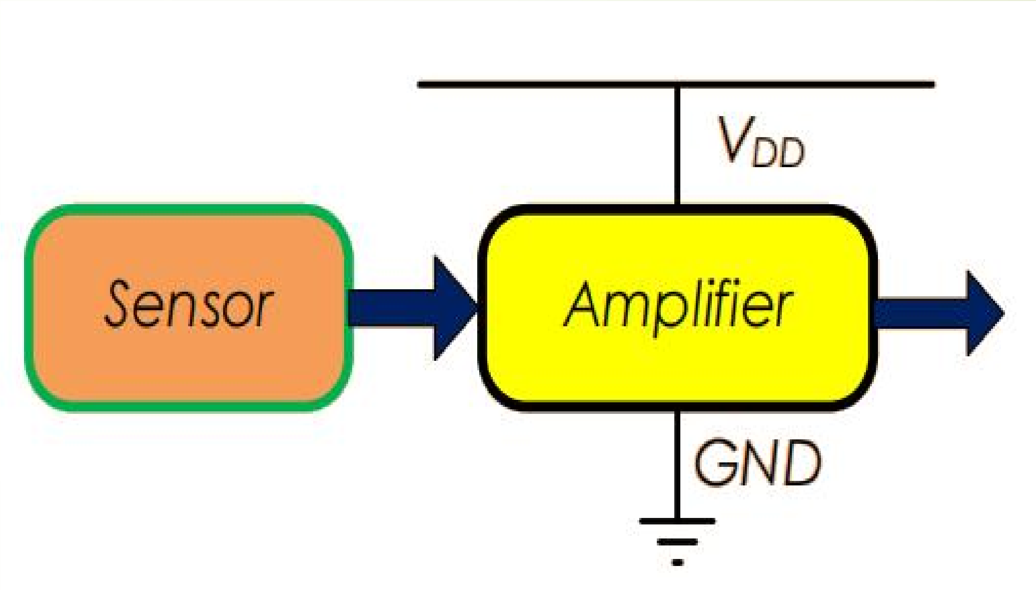
Displacement Sensors

Temperatue Sensor

Strain Gauge, etc.,

Active Sensors and Passive Sensors





Active Sensors

Passive Sensors

Displacement Sensors

Temperatue Sensor

Strain Gauge, etc.,

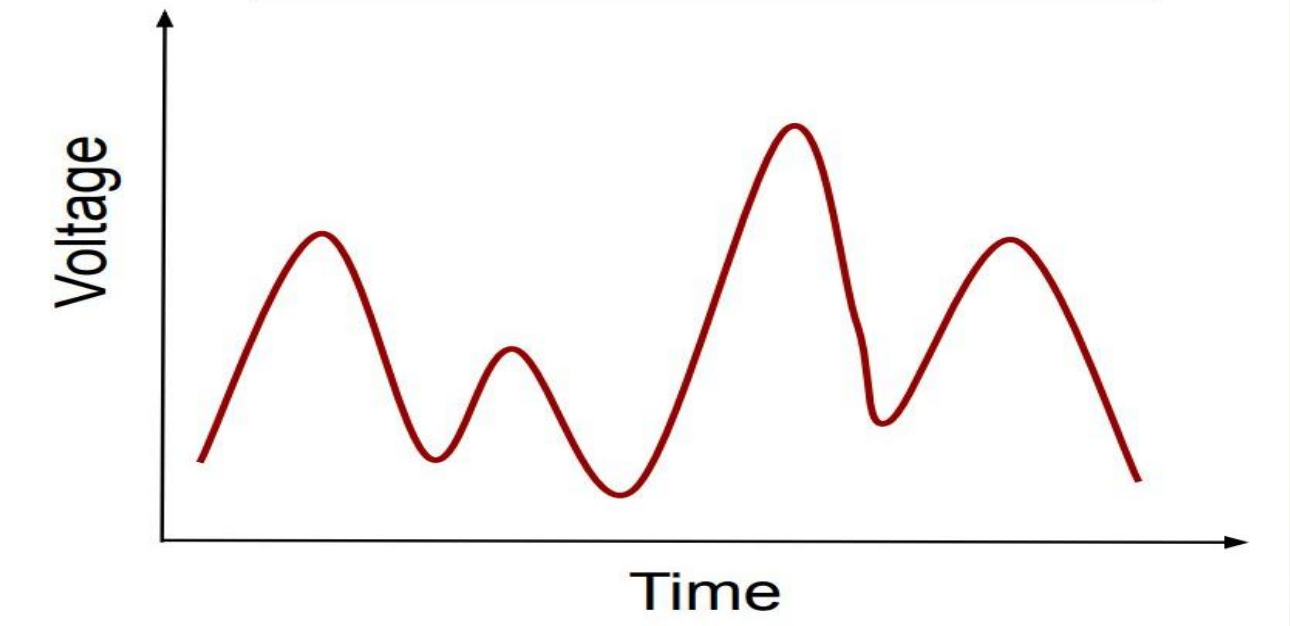
Piezoelectric Sensors

Thermocouples Strain

Photodiodes, etc.,

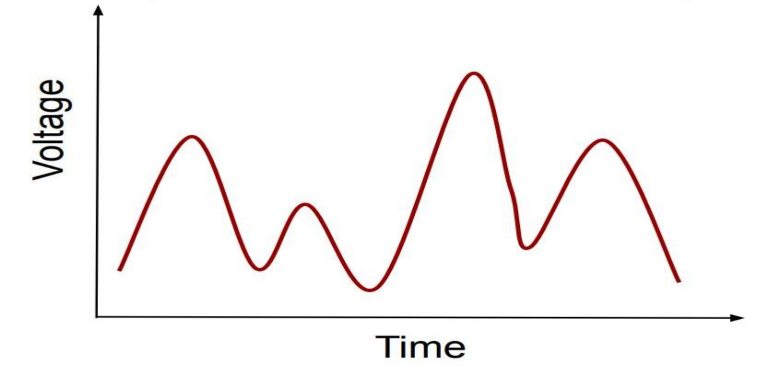
Analog and Digital Sensors

- **Analog Sensors** produce **continuous signals** that are propotional to the sensed parameter
- It requires analog to digital conversion before feeding to the digital controller.



Analog and Digital Sensors

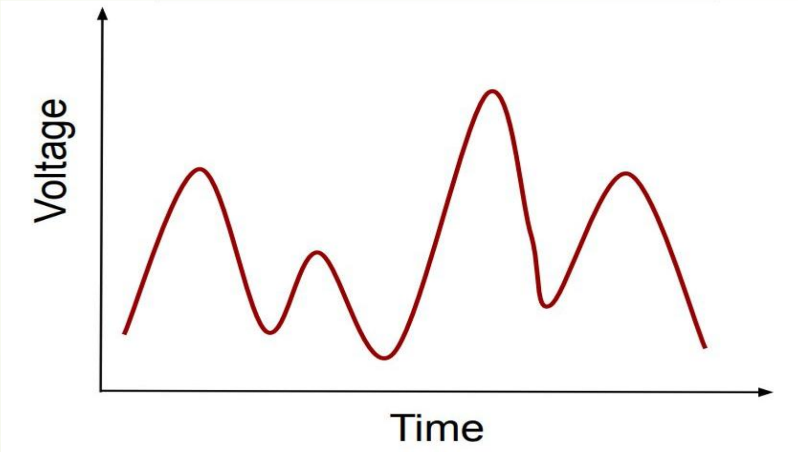
- **Analog Sensors** produce **continuous signals** that are propotional to the sensed parameter
- It requires analog to digital conversion before feeding to the digital controller.



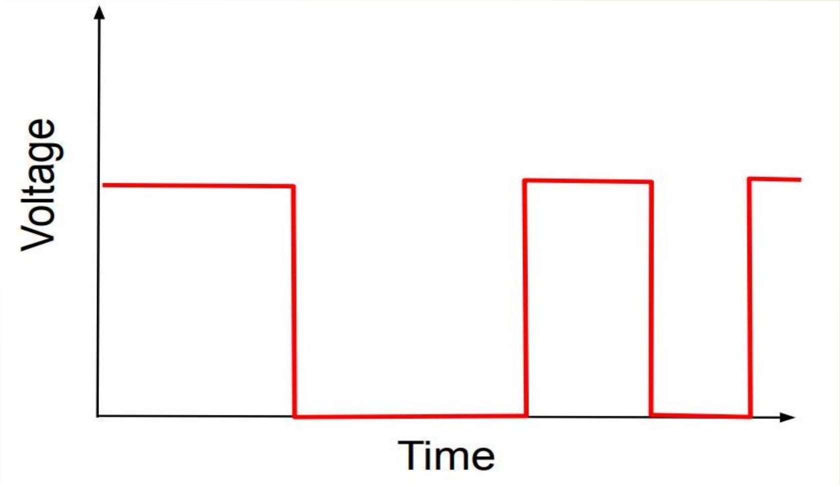
- **Digital Sensors** produce **digital outputs (0s and 1s)** that can be directly interfaced with the digital controller.

Analog and Digital Sensors

- **Analog Sensors** produce **continuous signals** that are propotional to the sensed parameter
- It requires analog to digital conversion before feeding to the digital controller.
- **Digital Sensors** produce **digital outputs (0s and 1s)** that can be directly interfaced with the digital controller.



Analog Sensors Output

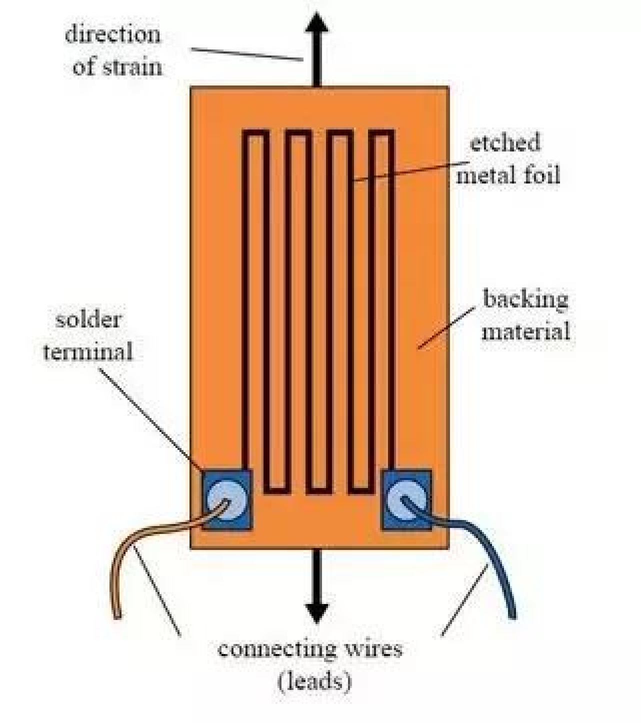


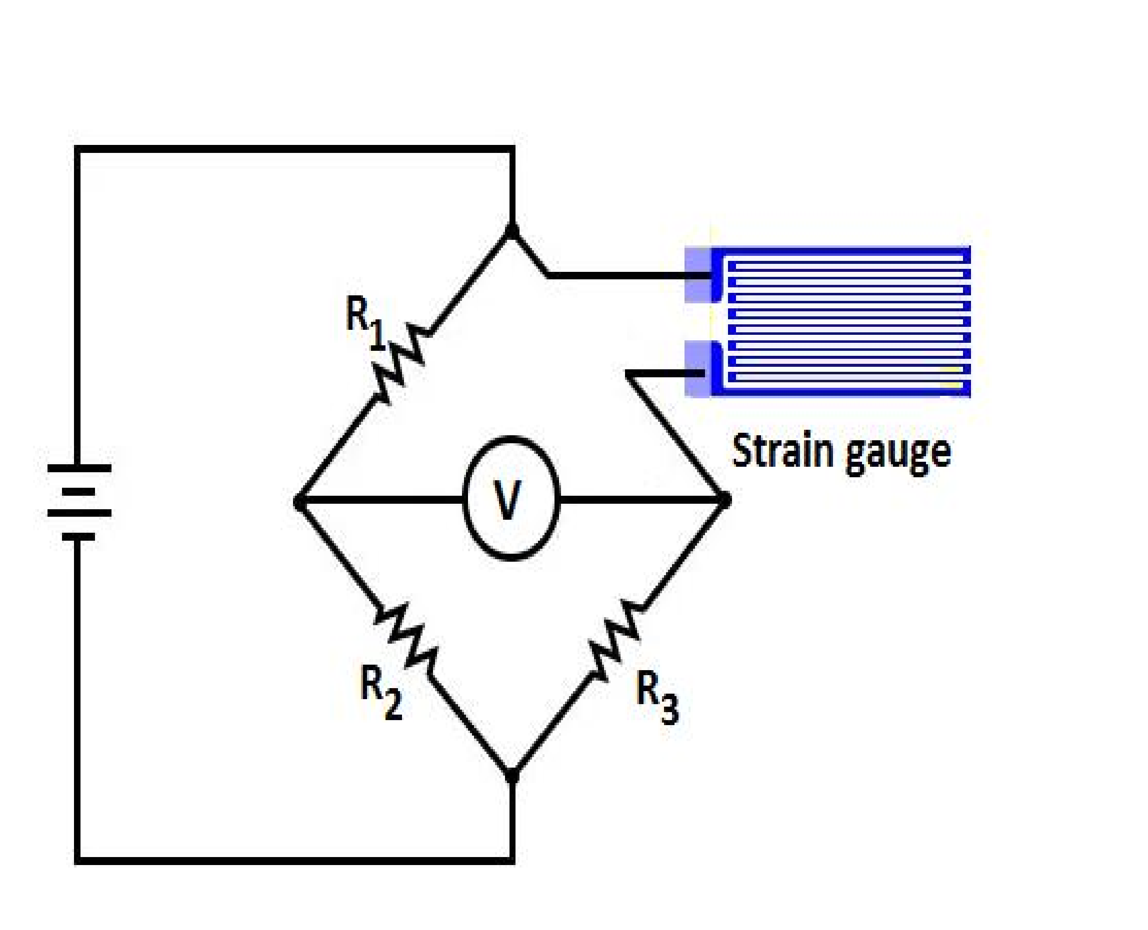
Digital Sensors Output

Mechanical Sensors

- Class of sensors to measure the mechanical phenomena
  - Pressure Sensor
  - Force and Torque Sensor
  - Inertial Sensor
  - Flow Sensor
- Mechanical Sensing Techniques
  - Piezoresistivity
  - Piezoelecricity
  - Capacitive Techniques
  - Inductive Techniques
  - Resonant Techniques

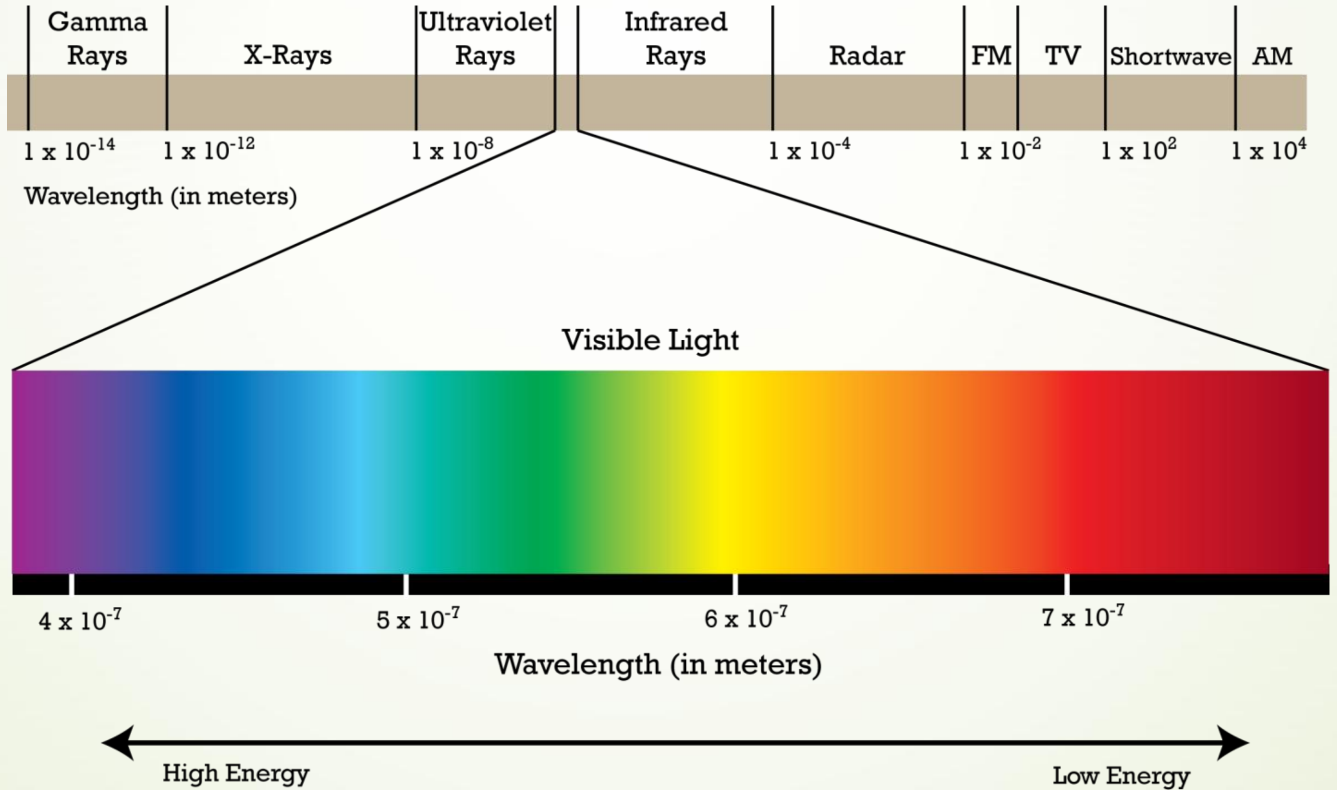
Mechanical Sensors





Optical Sensor

- Detect electromagnetic radiation in the broad optical range - from far infrared to ultraviolet
- Approximate range of wavelengths from 1mm ($3x10^{11}$ Hz or far infrared) to 1 nm ($3x10^{17}$ Hz or upper range of the ultraviolet range).



Optical Sensors

- Convert a ray of light into an electronic signal.
- Optical sensors are used for contact lens detection, counting, or part detection
- Optical sensors can be either internal or external.
- External sensors gather and transmit a required quantity of light, while internal sensors are most often used to measure the bends and other small changes in direction.
- Types of Optical Sensors
  - Point Sensor
  - Distributed Sensor

Optical Sensors

- Active pixel sensors
- Charged-coupled devices (CCD)
- Light-dependent resistors
- Photodiodes
- Phototransistors
- IR Sensors
- Fiber optic

Semiconductor Sensors

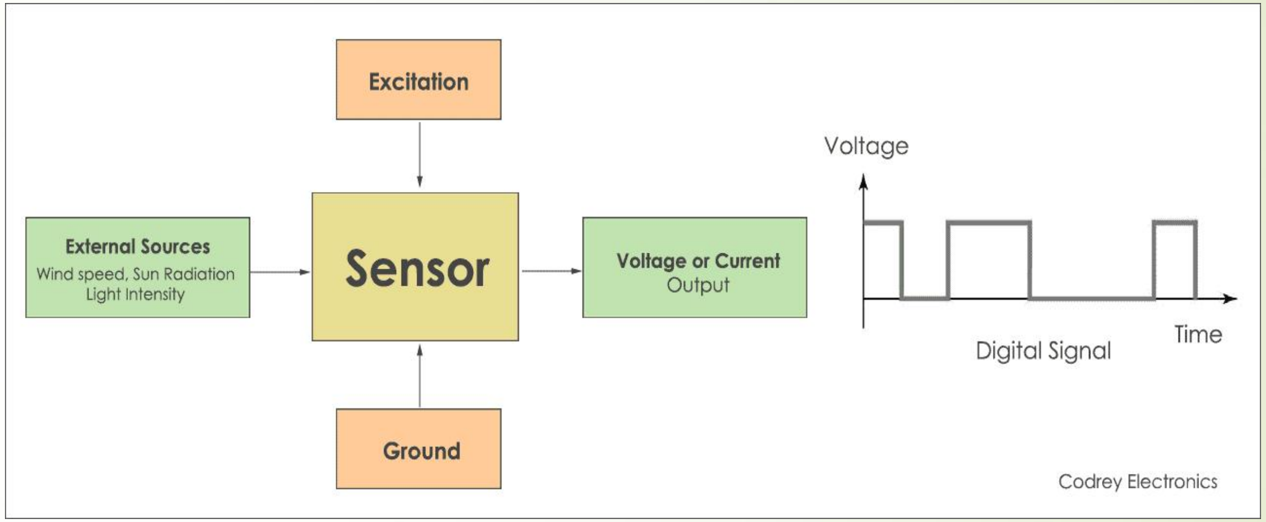
- Mostly used sensors
  - Low cost
  - Reliability
  - Low power consumption
  - long lifespan
- Semiconductor sensors are commonly used in
  - Gas monitoring
  - Pollution monitoring
  - Breath analyzers, etc.,

Electrochemical Sensors

- made on the basis of ion conduction
- based on electrical characteristics
  - potential sensors
  - conductivity sensors
  - electricity sensors
  - electrolytic sensors
- to analyze gas, liquid, or solid components dissolved in liquids

Digital Sensors

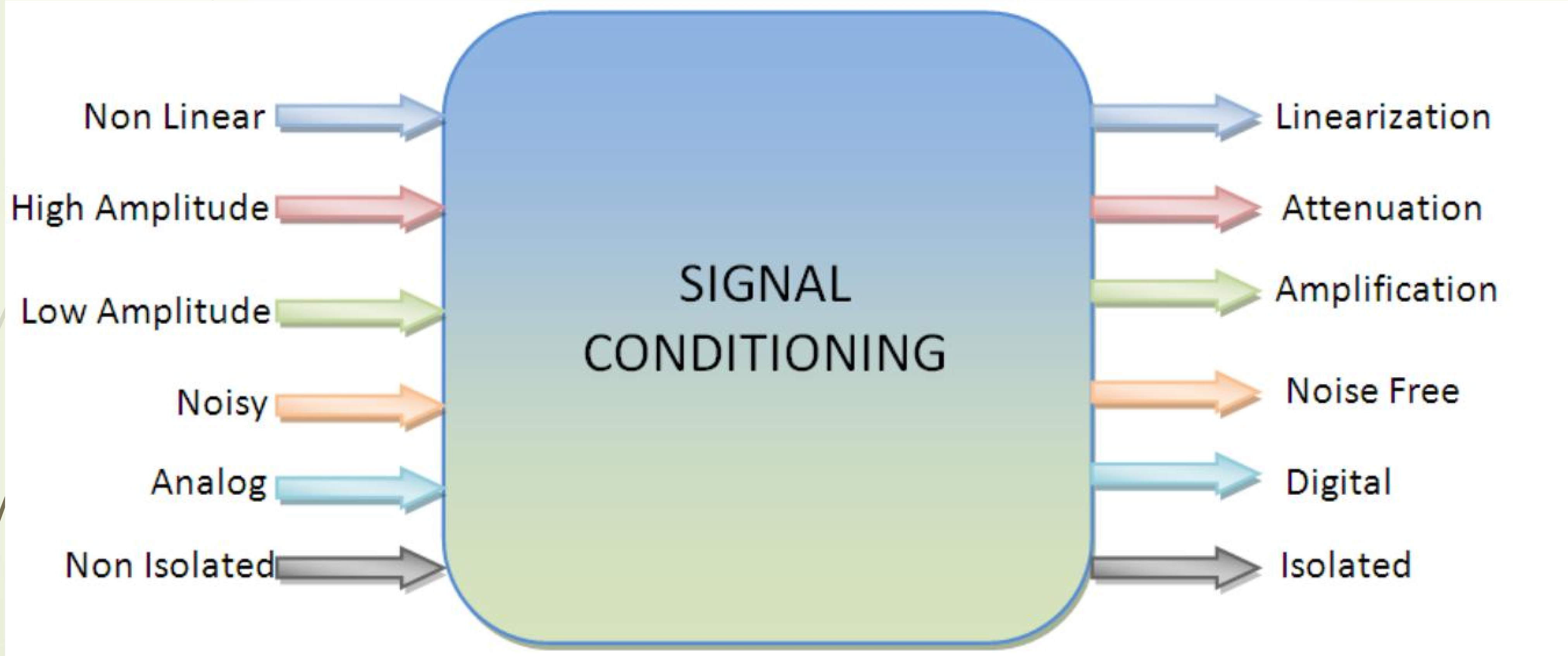
- Digital sensors are the kind of electrochemical or electrical sensors where the information is converted to digital form and then transmitted.



Signal conditioning

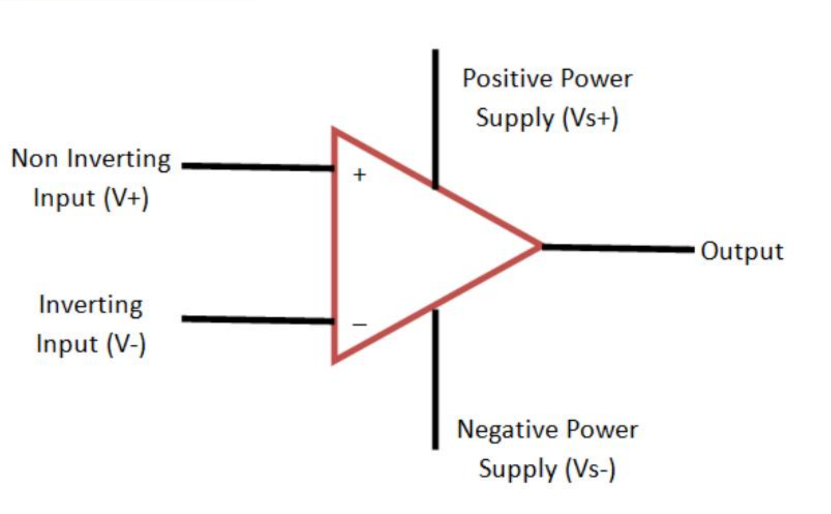
- Circuits are used to process the **output signal from sensors** of a measurement system to be **suitable for the next stage** of operation
- Signal conditioning circuits include
  - signal amplification
  - filtering
  - A/D converter
  - protection circuit
  - Linearization
  - error compensation

Signal conditioning



Signal conditioning-Amplification/Attenuation

- Sensors produce signals of the order of milli volts
- Most of the system (control action) accept voltage amplitudes in range of 0 to 10 Volts
- Low level input signals from sensors must be amplified to use them for further control action
- Operational amplifiers (op-amp) are widely used for amplification of input signals.



$$V_{out} = G(V^{+} - V^{-})$$

Signal conditioning-Non-inverting Amplifier

$$\frac{V_1 - 0}{R_1} = \frac{V_0 - V_1}{R_f}$$

Assume that the op-amp in the circuit is ideal op-amp,

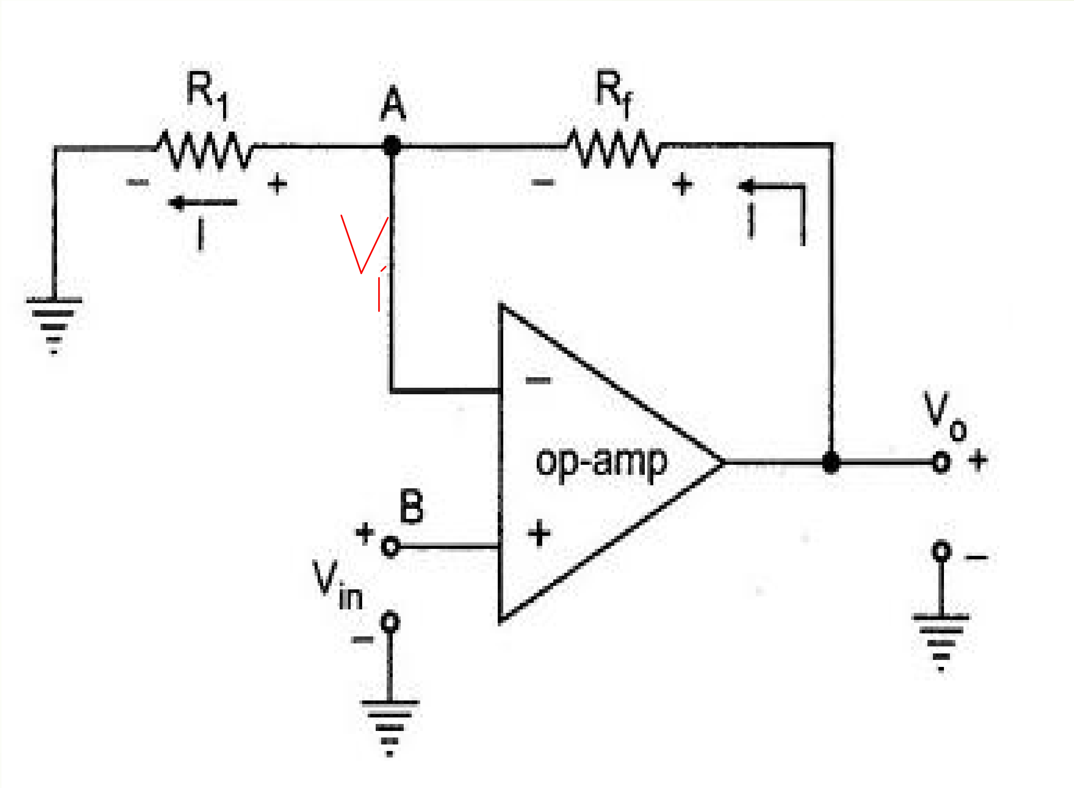
then, $V_{in} = V_1$

$$\frac{V_{in}}{R_1} = \frac{V_0 - V_{in}}{R_f}$$

$$\frac{V_{in}}{R_1} + \frac{V_{in}}{R_f} = \frac{V_0}{R_f}$$

$$V_{in}\left[\frac{1}{R_1} + \frac{1}{R_f}\right] = \frac{V_0}{R_f}$$

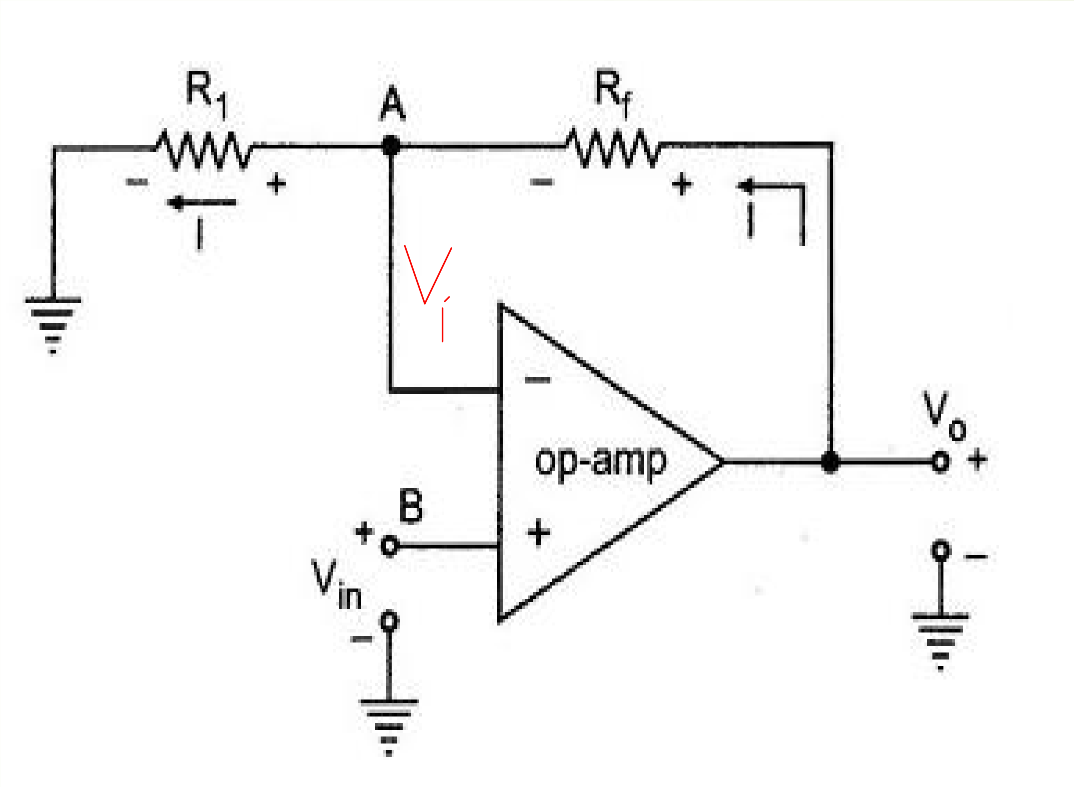
$$V_{in}\left[\frac{R_f + R_1}{\cancel{R_f} R_1}\right] = \frac{V_0}{\cancel{R_f}}$$



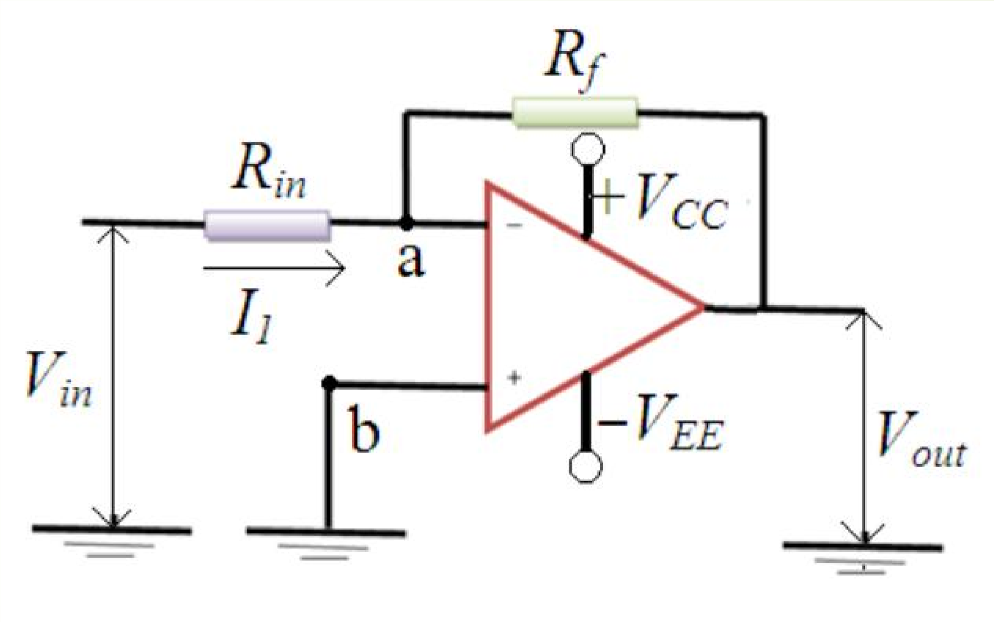
Signal conditioning-Non-inverting Amplifier

$$V_{in}\left[\frac{R_f + R_1}{\cancel{R_f} R_1}\right] = \frac{V_0}{\cancel{R_f}}$$

$$\boldsymbol{V_{in}\left[\frac{R_f}{R_1} + 1\right] = V_0}$$

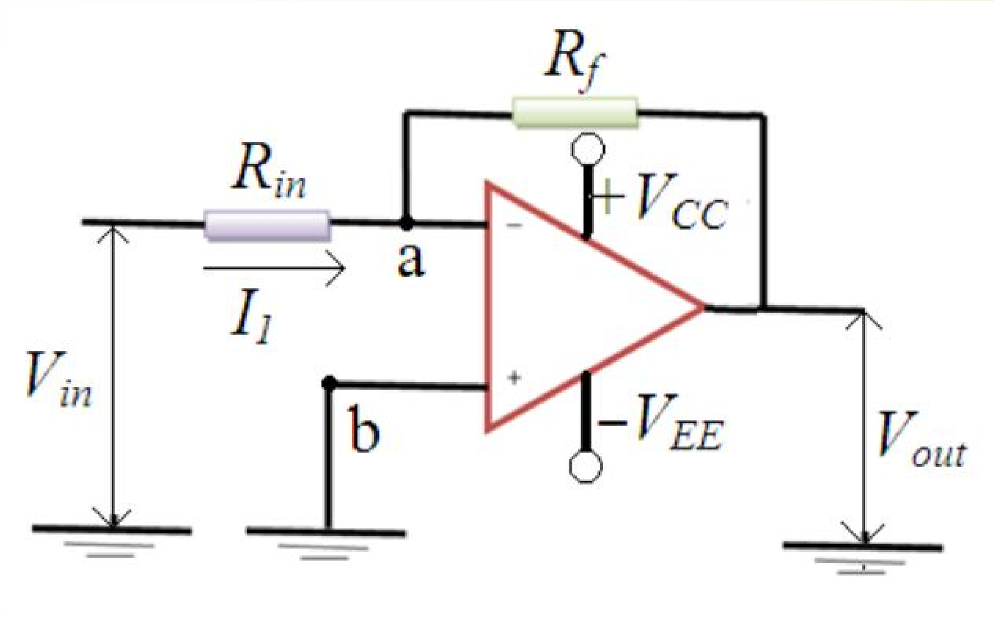


Signal conditioning-Inverting Amplifier



Signal conditioning-Inverting Amplifier

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

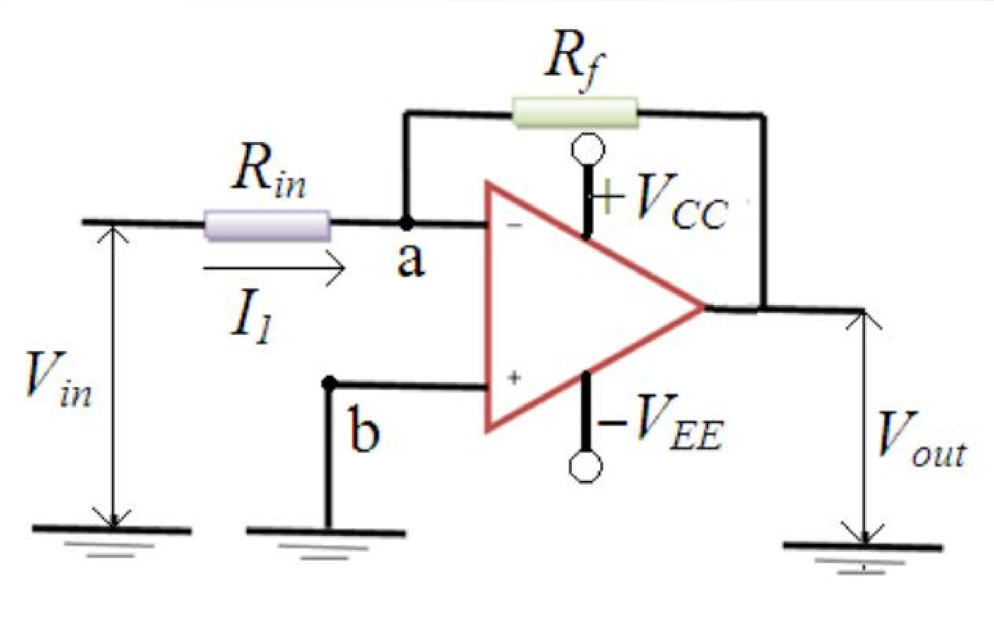


Signal conditioning-Inverting Amplifier

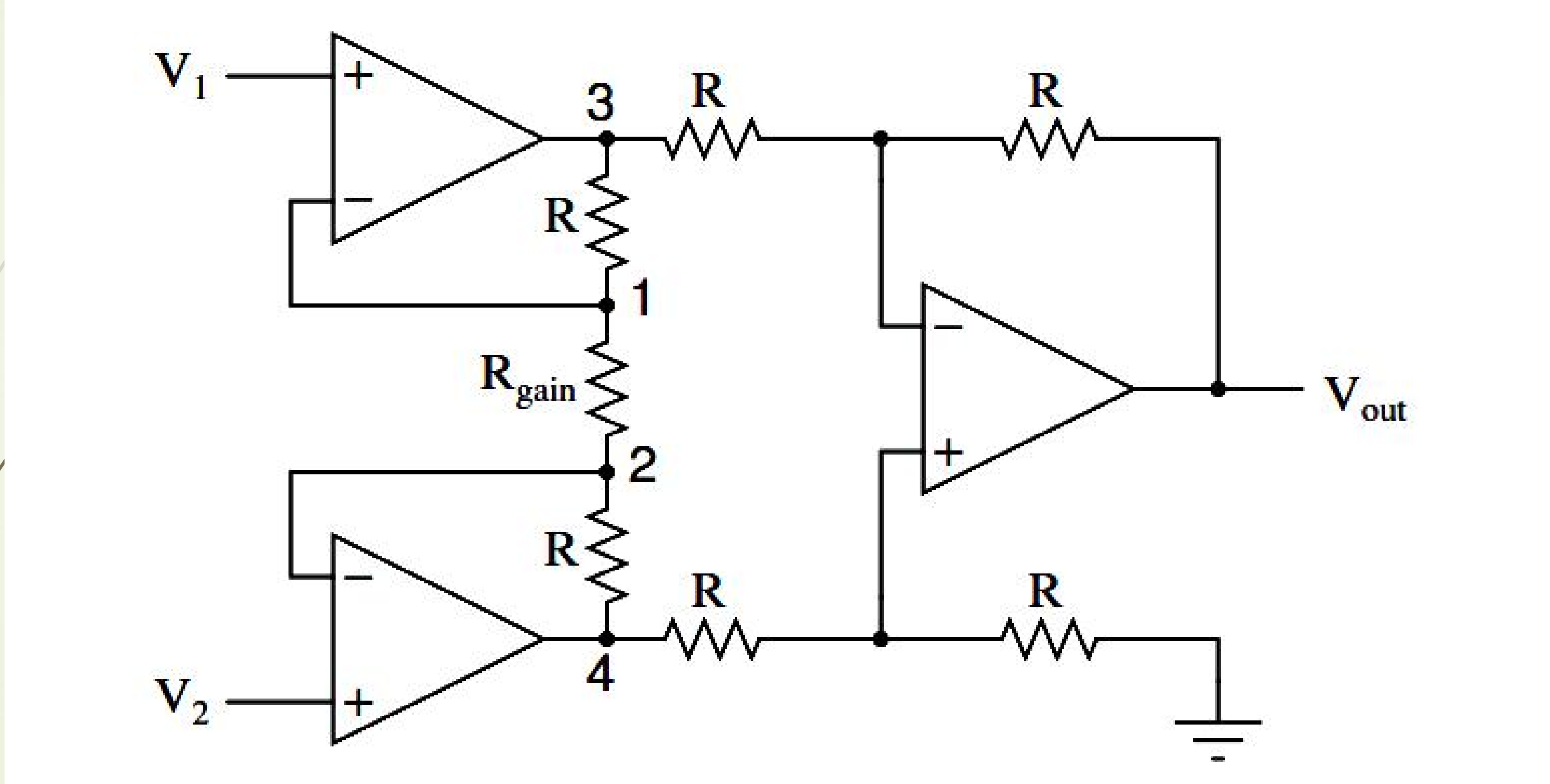
$$I_1 = \frac{V_{in}}{R_{in}}$$

$$V_{out} = -I_1 R_f$$

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



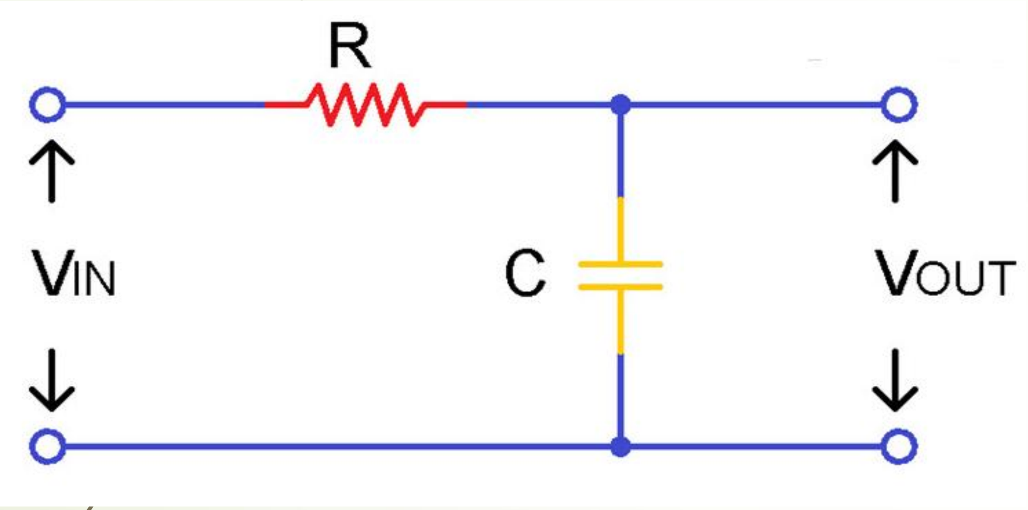
Signal conditioning- Instrumentation Amplifier



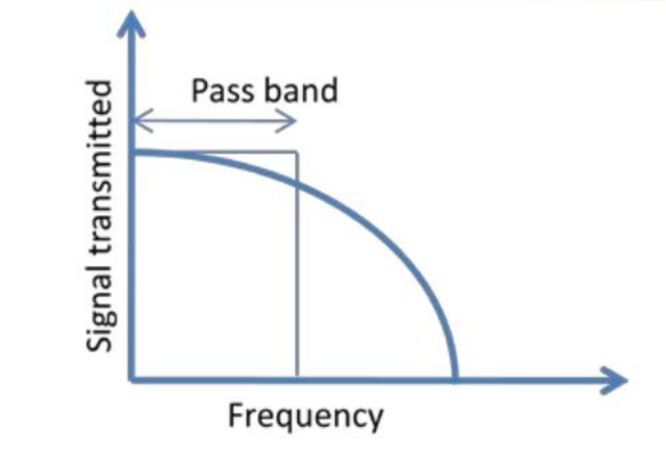
Signal conditioning-Filtering

- Output signals from sensors contain noise
  - improper hardware connections
  - environment etc.,
- Following types of filters are used in practice
  - Low Pass Filter
  - High Pass Filter
  - Band Pass Filter
  - Band Reject Filter

Signal conditioning-Low Pass Filter



Low PassFilter

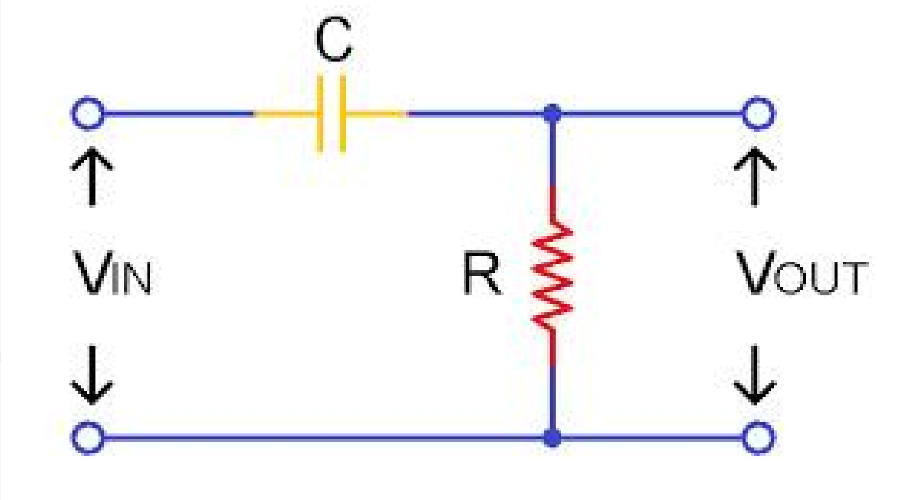


Pass Band for Low PassFilter

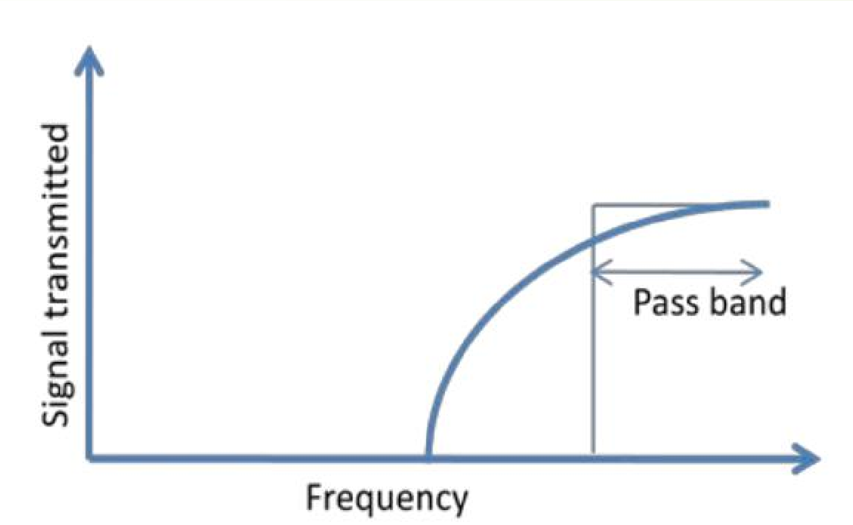
$$V_{out} = \frac{1/j\omega C}{R + \frac{1}{j\omega C}} V_{in}$$

$$\boldsymbol{V_{out} = \frac{1}{j\omega CR + 1} V_{in}}$$

Signal conditioning-High Pass Filter

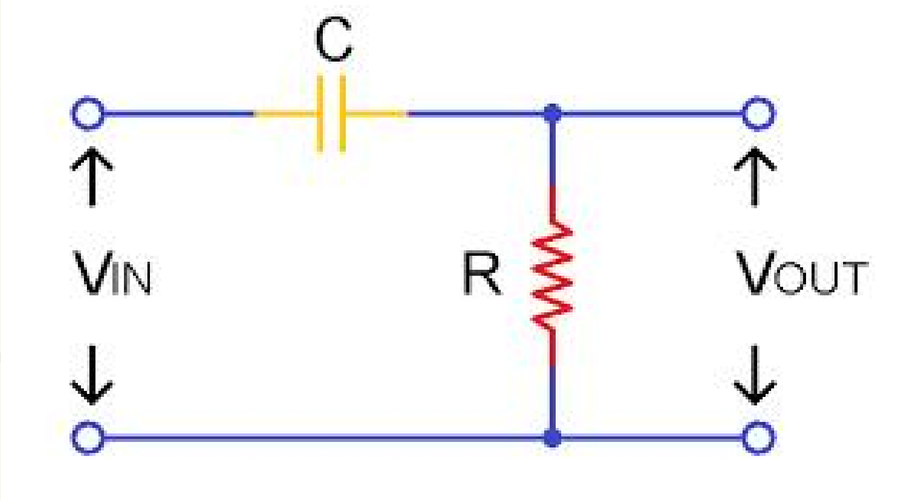


High PassFilter

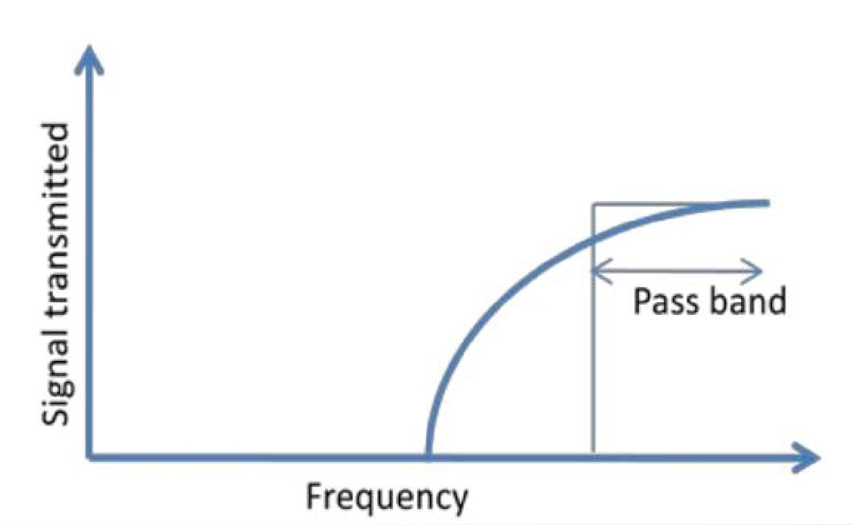


Pass Band for High PassFilter

Signal conditioning-High Pass Filter



High PassFilter

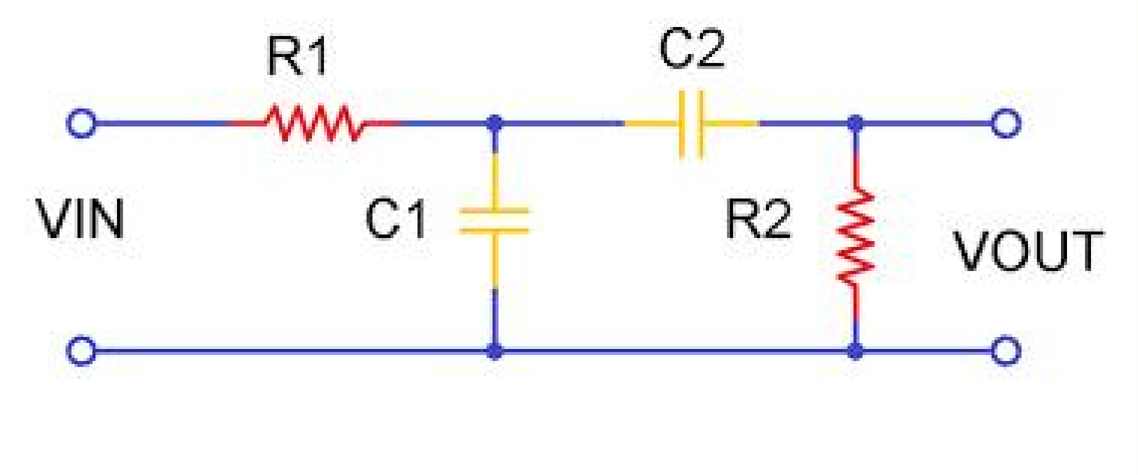


Pass Band for High PassFilter

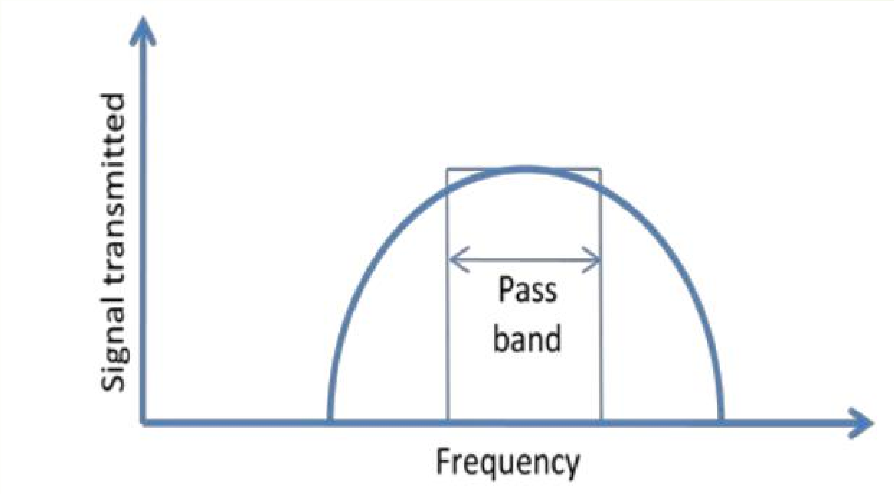
$$V_{out} = \frac{R}{R + \frac{1}{j\omega C}} V_{in}$$

$$\boldsymbol{V_{out} = \frac{j\omega RC}{j\omega CR + 1} V_{in}}$$

Signal conditioning-Band Pass Filter

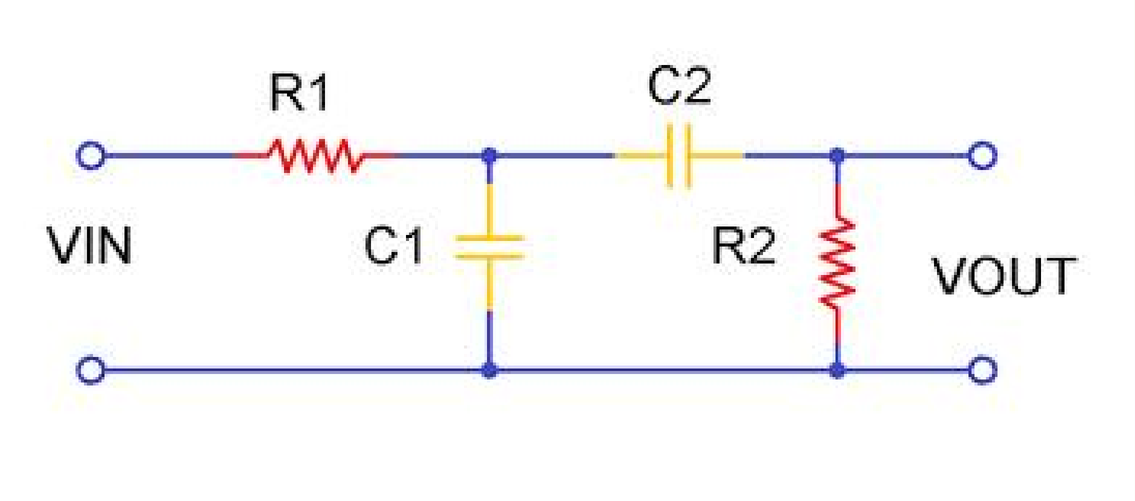


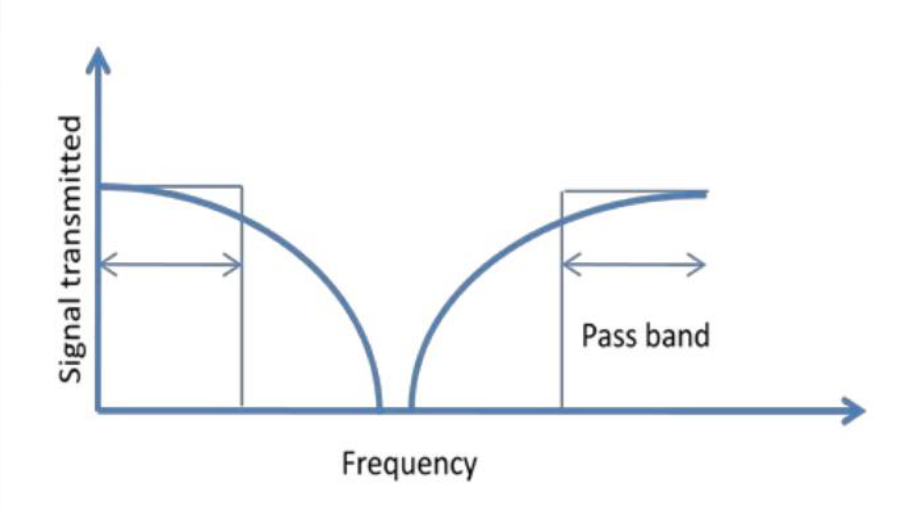
Band PassFilter



Pass Band for Band PassFilter

Signal conditioning-Band Stop Filter



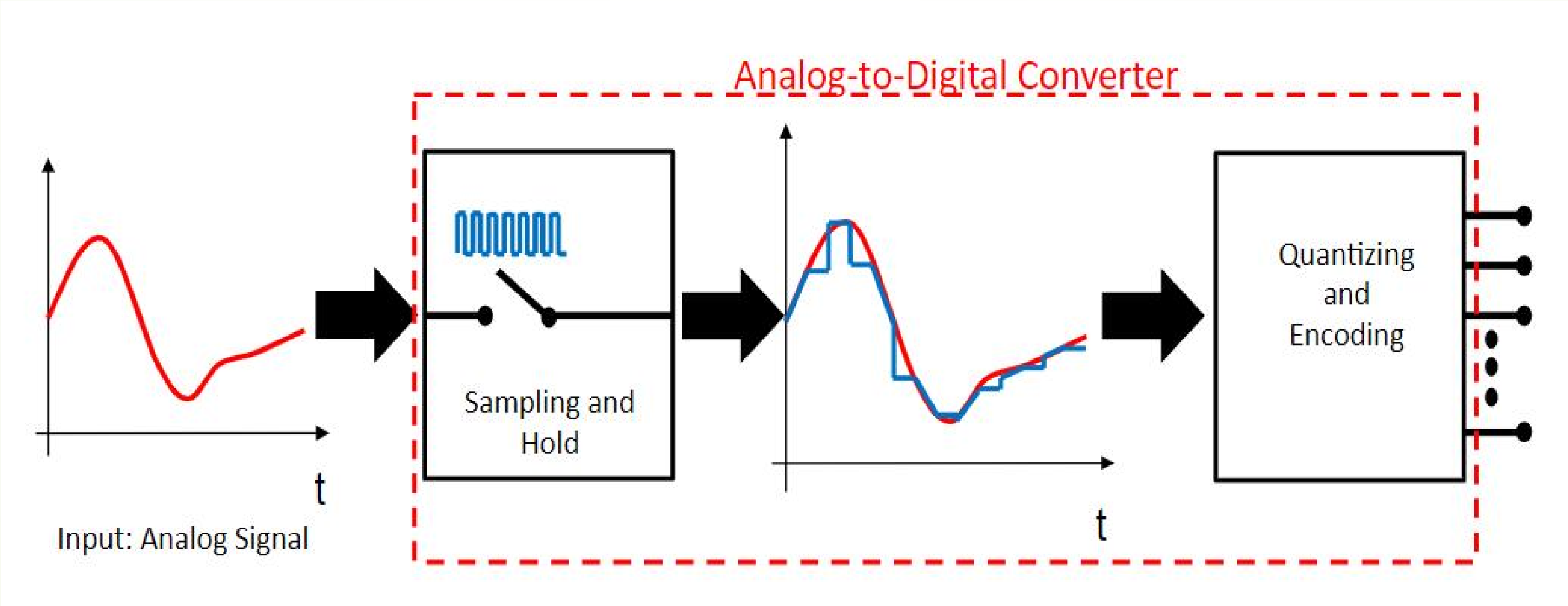


Band Stop Filter

Pass Band for Band Stop Filter

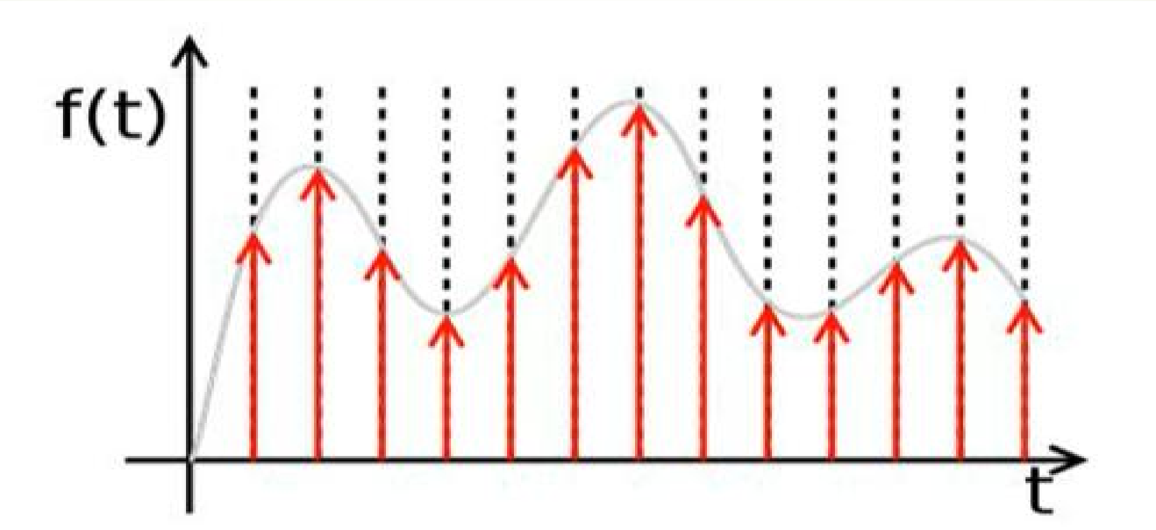
Analog to Digital Converter

- used to convert an analog (continuous)signal such as voltage to a digital (discrete) form
- Three main step of process
  - Sampling and Holding
  - Quantization
  - Encoding



Analog to Digital Converter Sampling

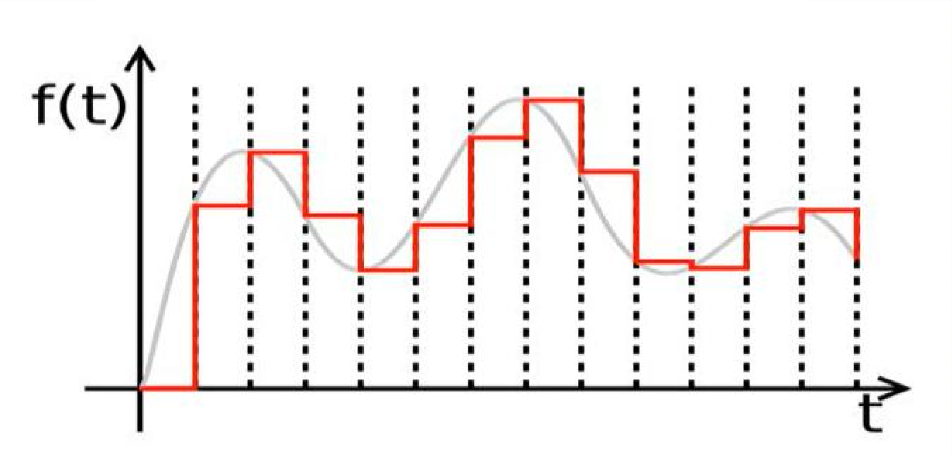
- The analog signal is sampled at regular intervals of time



- The sampling rate must be at least twice the highest frequency of the signal. (Nyquist Criterion)

Analog to Digital Converter - Quantization

- Process of converting the continuous sample amplitude into discrete amplitude

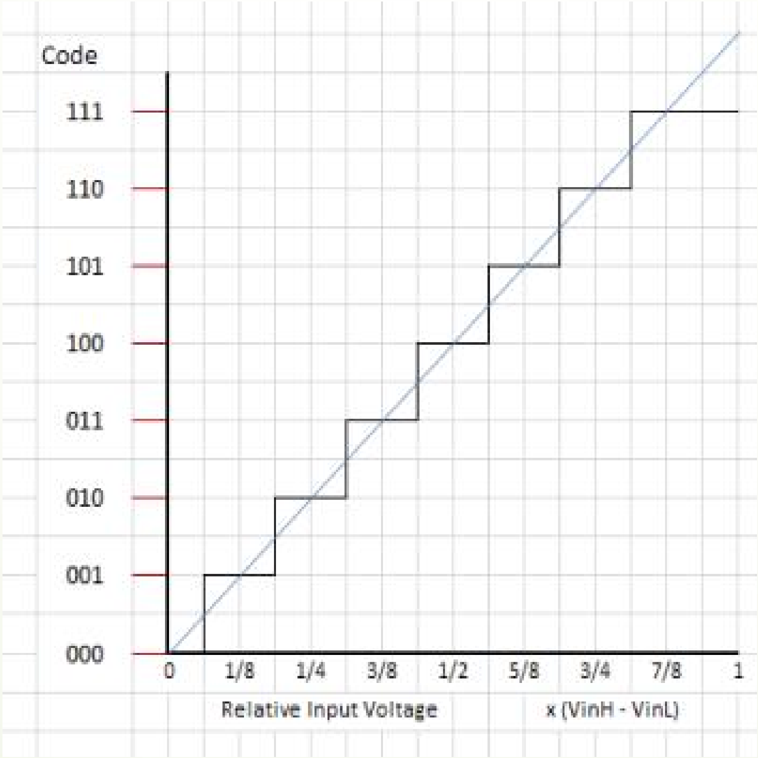


- After this, the signal will be discrete in both time and amplitude

Analog to Digital Converter - Encoding

- Assigns ones and zeros for every quantization level
- Number of bits assignedfor each level depends on the level’s number L

$$L = 2^n$$



Types of ADC

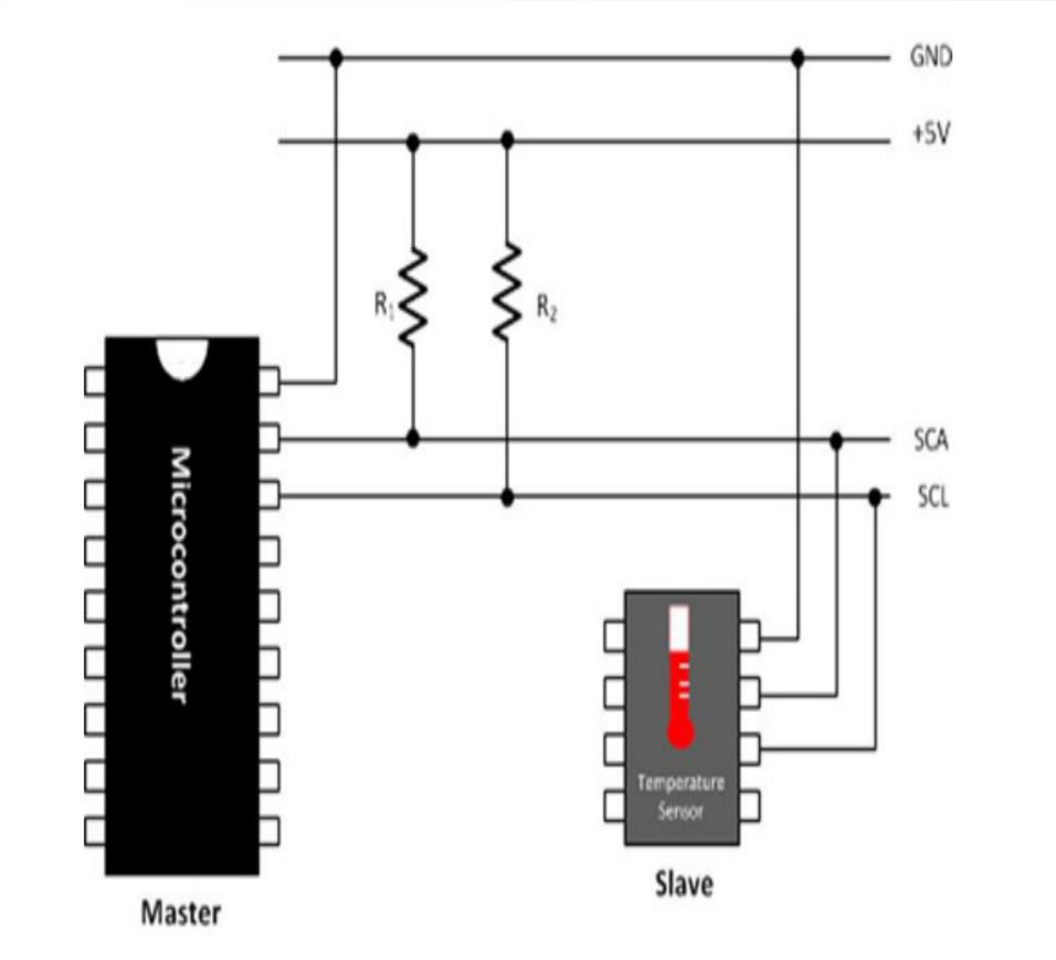
- Direct ADC
- Successive Approximation Register (SAR)ADC
- Integrating ADCs
    - Single Slope
    - Dual Slope
    - Ramp ADC
- Sigma-Delta ADC

I^2C

- To facilitate lowbandwidth serial communications

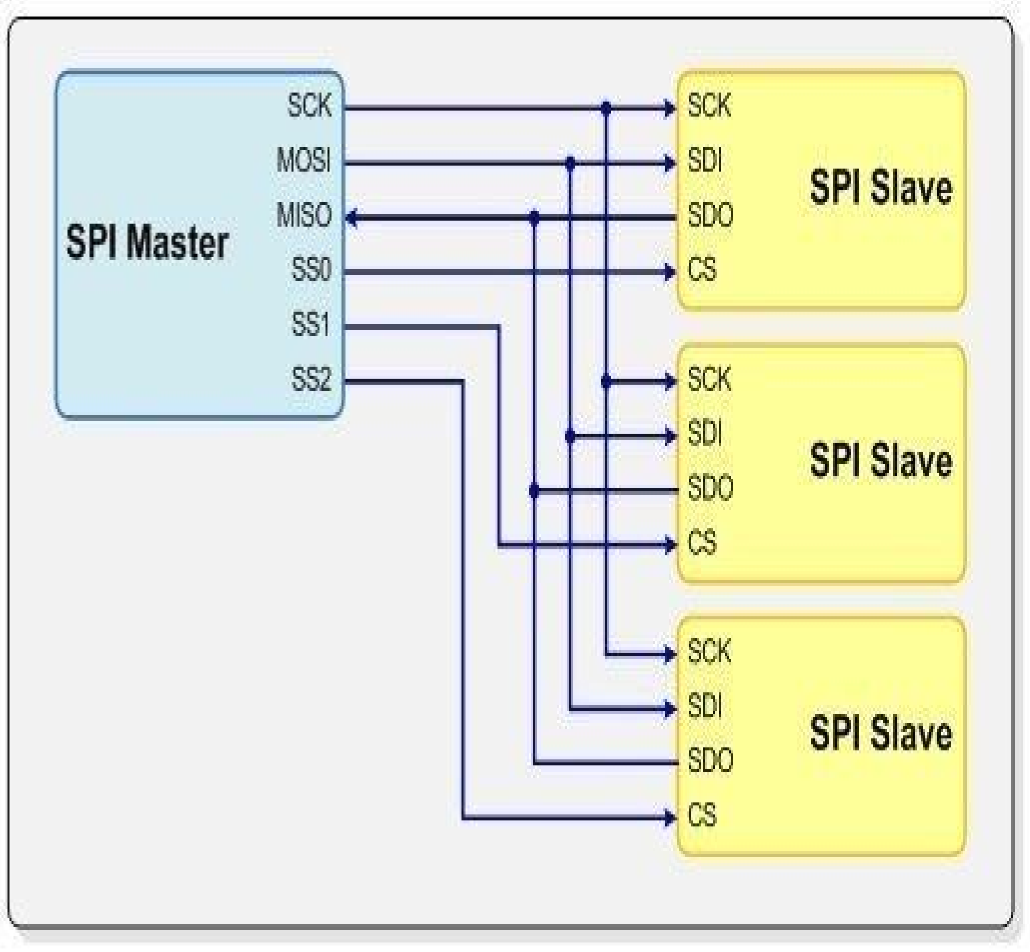
between components residing on the same PCB.

- It operates in a multi-master mode over short distances
- I^2C bus is a two-wire bidirectional bus one wire carries a **clock signal** and the other **carries the data**
  - **Speed of data transfer**
  - **100 kbps - Standard Mode**
  - **400 kbps - Fast Mode**
  - **3.4 Mbps - High speed Mode**



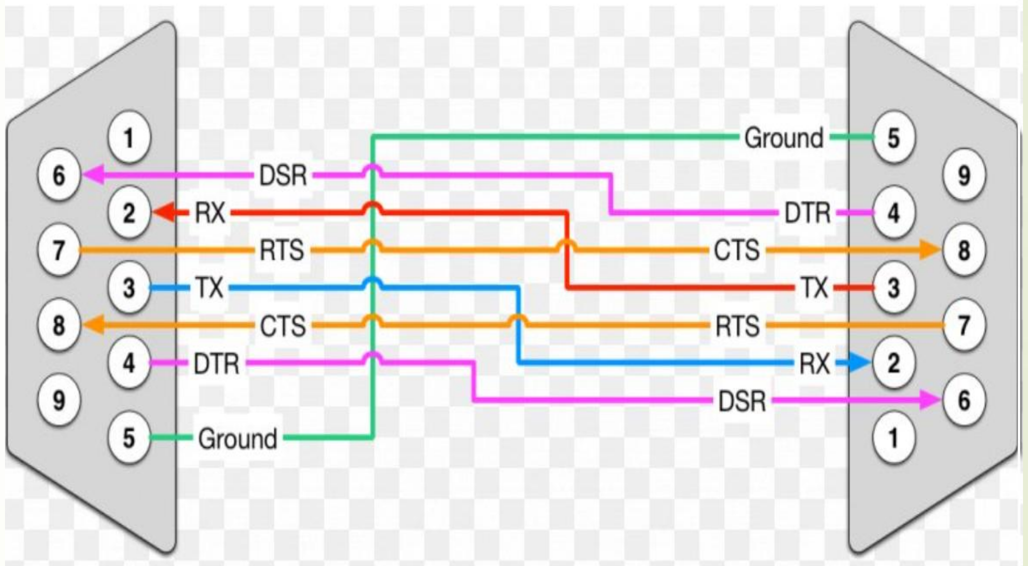
Serial Peripheral Interface

- SPI (Serial Peripheral Interface) is a **full duplex** synchronous serial communication interface used for short distance communications
- used for communication between **different modules in a same device** or **PCB**
- **communicates each other** using a **master slave architecture** with a single master.
- Communicate with serial peripheral devices, such as digital sensors



RS-232

- serial bus consists of just **two communication wires** - one for sending data and another for receiving.
- It is the physical interface and protocol for relatively **low-speed serial data communication** between computers and related devices
- data is sent serially, each bit is sent one after the next because there is only one data line in each direction.
- Both **synchronous and asynchronous transmissions** are supported by the standard



Serial Communication

	RS-232	RS-422	RS-485
Cable	Single ended	Single ended multi-drop	Multi-drop
Number of Devices	1 transmitter 1 receiver	1 transmitter 10 receivers	32 transmitters 32 receivers
Communication Mode	Full duplex	Full duplex, Half duplex	Full duplex, Half duplex
Maximum Distance	50 feet at 19.2 kbps	4000 feet at 100 kbps	4000 feet at 100 kbps
Max Data Rate (50 feet)	1 mbps	10 mbps	10 mbps