SENSORS AND ACTUATORS

Sensors

- A sensor detects and responds to some type of input from the physical environment.
- Devices that detect physical quantities (e.g., temperature, pressure, light) and convert them into measurable signals.
- Inputs can include light, heat, motion, moisture, force, pressure, displacement, etc.
- It produces a proportional output signal (electrical, mechanical, magnetic, etc.).
- Types of Sensors
  - Analog Sensors:

    Provide continuous output signals (e.g., temperature sensors).
  - Digital Sensors:

    Provide discrete output signals (e.g., digital accelerometers).
  - Active and Passive Sensors:
    - Active: Require external power (e.g., ultrasonic sensors).
    - Passive: Do not require external power (e.g., thermocouples).

Is it necessary that every sensor converts measured quantity into electrical signal?

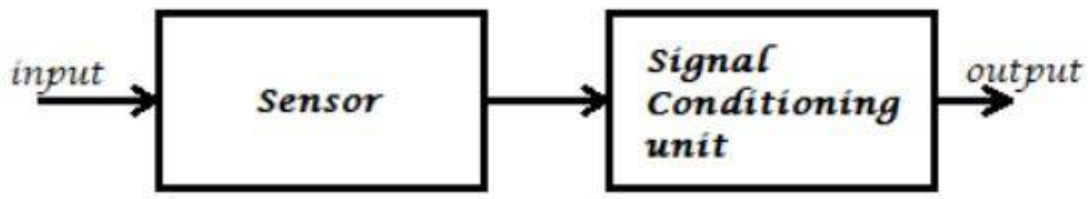
- Human Beings have 5 different Sensors:
  - Eyes detect light energy.
  - Ears detect acoustic energy.
  - Tongue and nose detect certain chemicals.
  - Skin detects pressure and temperature.
- The eyes, ears, tongue, nose, and skin receive these signals and send messages to the brain.
- The brain processes these inputs and generates a response.
- Example:
  - When you touch a hot plate, your brain tells you it is hot, not your skin.
  - When you smell food, your brain identifies the scent and may trigger hunger or memories associated with that smell.

Working Principle

- **Input: Physical Quantity**
  - Sensors are designed to detect specific physical quantities from the environment.
  - Examples of physical quantities:
    - **Light** (e.g., brightness, color).
    - **Heat** (e.g., temperature).
    - **Pressure** (e.g., force applied).
    - **Motion** (e.g., acceleration, velocity).
    - **Sound** (e.g., frequency, intensity).
- **Transduction: Conversion into Electrical Signals**
  - The core function of a sensor is **transduction**, which is the process of converting a physical quantity into an electrical signal.
  - This is achieved through various mechanisms depending on the type of sensor:
    - **Resistive Change:** Physical change alters resistance (e.g., LDR, strain gauge).
    - **Capacitive Change:** Physical change alters capacitance (e.g., touch sensors).
    - **Piezoelectric Effect:** Mechanical stress generates voltage (e.g., pressure sensors).
    - **Photoelectric Effect:** Light energy generates electrical signals (e.g., photodiodes).

- **Output: Measurable Signal**
  - The electrical signal produced by the sensor is then measured and interpreted.
  - Common types of output signals:
    - **Voltage** (e.g., thermocouples).
    - **Current** (e.g., phototransistors).
    - **Resistance** (e.g., LDR, thermistors).
    - **Frequency** (e.g., ultrasonic sensors).
  - These signals are often processed by microcontrollers or computers for further action.

Block diagram of a sensor



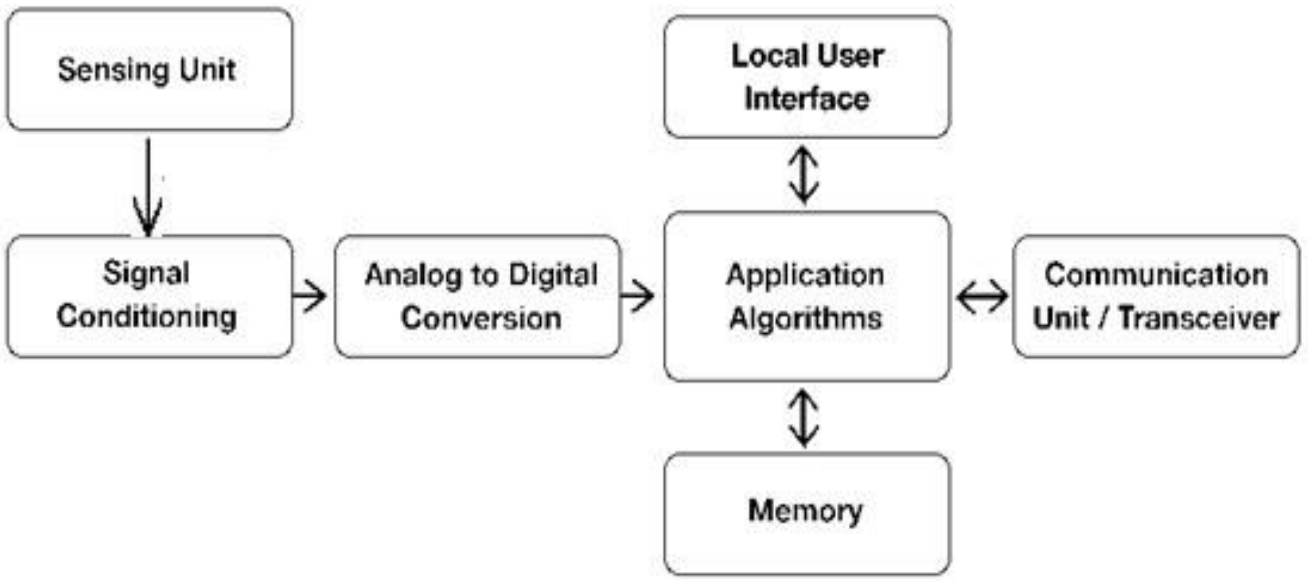
Block diagram of a Smart Sensor

- **Sensing Unit**

  This unit detects the changes in physical parameters & generates electrical signals equivalent to it.

- **Signal Conditioning Unit**

  The signal conditioning unit controls the signal to meet the necessities of next-level operations without losing data.



- **Analog to Digital Conversion** converts the signal from analog to digital format & sends it to the microprocessor.

- **Local User Interface** The local user interface or LUI is a panel-mounted device used to allow building operators to monitor & control system equipment

- **Application Algorithm** The signals from smart sensors reach here & process the received data based on the application programs previously loaded here & generate output signals.
- **Memory** It is used to store media for saving received & processed data.
- **Communication Unit** The output signals from the application algorithm or microprocessor are transmitted to the main station through the communication unit. This unit also gets command requirements from the key station to execute specific tasks.

Characteristics

- **Range** It is the difference between the maximum and minimum value of the sensed parameter. Temperature range of a thermocouple is 25-225°C.

- **Resolution** The smallest change the sensor can differentiate. It is also frequently known as the least count of the sensor. Resolution is an important factor for accuracy of measurement.

- **Sensitivity** A measure of minimum detectable input.
  - It is the ratio of change in output to a unit change of the input.
  - The sensitivity of digital sensors is closely related to the resolution.
  - The sensitivity of an analog sensor is the slope of the output vs input line, or sensor exhibiting truly linear behavior has a constant sensitivity over the entire input range

$$Sensitivity(S) = \frac{change\ in\ output}{unit\ change\ in\ input}$$

- **Accuracy** is defined as the difference between the measured value and the true value. Is refers to the closeness between the actual measured value and a true value. It is used to determine errors in measurement.

$$Absolute\ Error = |Measured\ Value\ - True\ Value|$$

$$Relative\ error = \frac{Absolute\ Error}{True\ Value}$$

- Example of Error Calculation:
  - The actual temperature of a room is 24°C
  - A measurement instrument detects it as 26°C.
- Absolute Error Calculation:

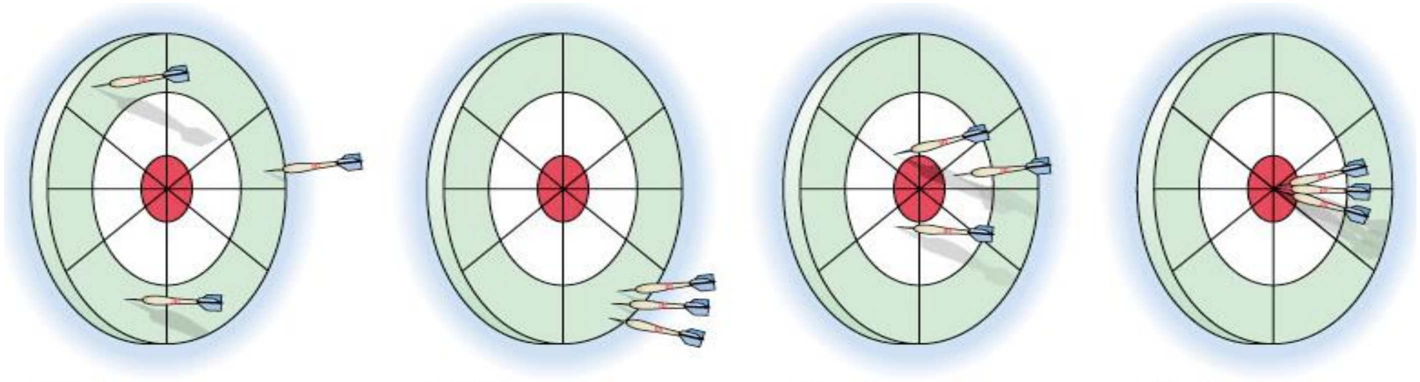
$$Absolute\ Error = |26°\text{C} - 24°\text{C}| = 2°\text{C}$$

- Relative Error Calculation:

$$Relative\ Error = 2°\text{C}/24°\text{C} = 0.083$$

So, this system has 8.3 % error or we can say that the system is 91.7 percent accurate.

- **Precision** is defined as the closeness among different set of measured values. It is related to the measurement of a set of measurements.
- It is not necessary that if a system has good precision will have good accuracy.
- Precision defines closeness among a set of different measured values while accuracy refers to the closeness of a measured value with the true value
- Let X_t be the true value of the variable X and random experiments measure values X_1, X_2, X_3,…. X_n as values of X. If X_1= X_2= X_3=…. = X_n, then we can say that the measurement procedure is precise.



(a) Low accuracy Low precision

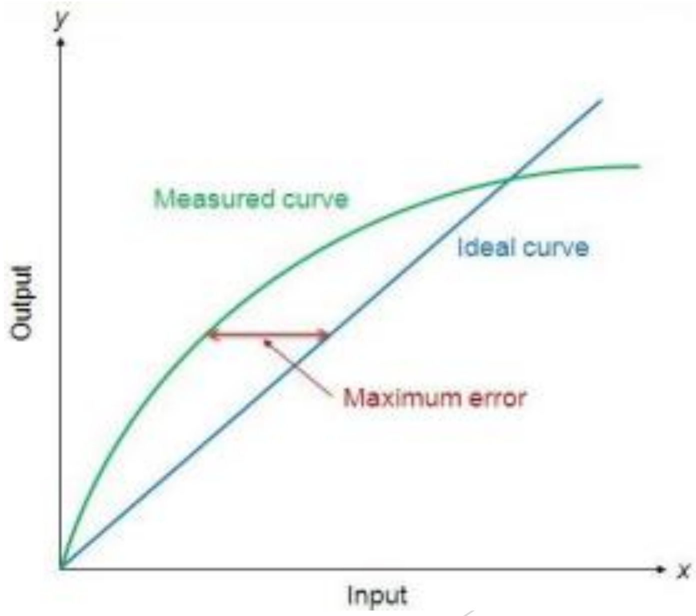
(b) Low accuracy High precision

(c) High accuracy Low precision

(d) High accuracy High precision

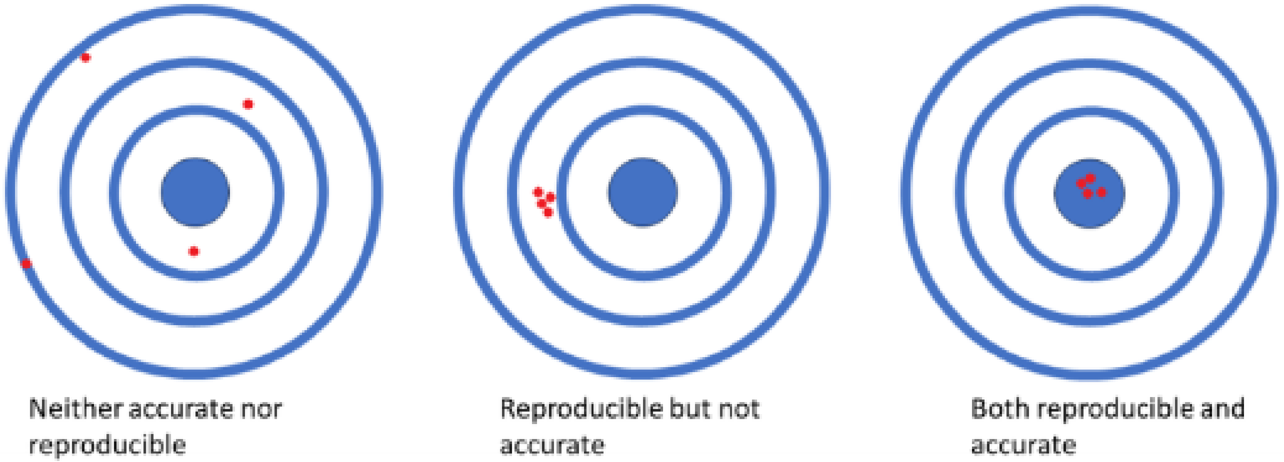
- **Linearity** refers to the ability of a measurement system or sensor to react uniformly to changes in a measured variable over a specified range.
- Degree to which a device's output curve resembles a straight line is referred to as the linearity of an instrument's output. It really serves as a gauge for the output's nonlinearity.
- **Linearity Error or Non-Linearity** Percentage of deviation from the best fit linear calibration curve.
- The nonlinearity indicates the maximum deviation of the actual measured curve of a sensor from the ideal curve.

$$Non - Linearity(\%) = \frac{Maximum\ deviation\ in\ input}{Maximum\ Full\ Scale\ Point}$$



- **Repeatability** refers to the ability of a measurement system or sensor to produce the **same output** when the same input is applied multiple times **under the same conditions**.
- The conditions are as follows:
  - At the same place
  - By the same person
  - By the same method
  - Using the same equipment
  - Over the short period of time
- Suppose a land is measured 8 times with following readings: 250, 254, 249, 253, 245, 250, 251, 248. Standard Deviation:
  - $Mean(\mu) = average\ of\ all\ readings = 250$
  - $Variance\ (\sigma^2) = \frac{\sum(X_i - \mu)^2}{N} = \frac{0^2+4^2+(-1)^2+3^2+(-5)^2+1^2+(-2)^2}{8} = \frac{56}{8} = 7$
  - $Standard\ Deviation(\sigma) = \sqrt{7} = 2.65$

- **Reproducibility** describes how well a sensor can produce consistent results when measuring the same quantity under different conditions or in different environments. In other words, it measures the consistency of the sensor's output across multiple tests or trials.
- Reproducibility refers to the ability of a measurement, experiment, or system to produce **consistent results** when performed **by different people, using different equipment, or at different locations** under similar conditions.



- **Response Time** is the amount of time required for a sensor to respond completely to a change in input.
  - It describes the speed of change in the output on a step-wise change of the measurand.
  - Often expressed as the time it takes for the sensor output to reach a certain percentage (like 90%).

- **Dead Band** It is insensitivity of a sensor in a specific range of the input signals.
  - In that range, the output may remain near a certain value (often zero) over an entire dead band zone.
  - The dead time of a sensor device is the time duration from the application of an input until the output begins to respond or change

- **Error** is the difference between a measured value and the true input value.
- Two classifications of errors are bias (or systematic) errors and precision (or random) errors.
  - Bias errors are present in all measurements made with a given sensor, and cannot be detected or removed by statistical means. It is a **systematic error** that causes measurements to be consistently **offset** from the true value. It represents a deviation in one direction due to factors like instrument calibration issues or environmental conditions.
  - These bias errors can be further subdivided into:
    - *calibration errors* (a zero or null point error is a common type of bias error created by a nonzero output value when the input is zero),
    - *loading errors* (adding the sensor to the measured system changes the system), and
    - errors due to sensor sensitivity to variables other than the desired one (e.g., temperature effects on strain gages).

Classification of Sensors

- Based on the Type of Input Signal (Measured Quantity)
- Based on Output Type
- Based on the Sensing Principle
- Based on Power Requirement
- Based on Applications

Based on the Type of Input Signal (Measured Quantity)

- **Temperature Sensors**: Thermocouples, RTDs, Thermistors, Infrared sensors
- **Proximity Sensors**: Inductive, Capacitive, Ultrasonic, IR sensors
- **Optical Sensors**: Photodiodes, Phototransistors, LDRs
- **Pressure Sensors**: Strain gauges, Piezoelectric sensors
- **Humidity Sensors**: Capacitive, Resistive, Thermal conductivity sensors
- **Position Sensors**: Potentiometers, Encoders, Hall effect sensors
- **Acceleration Sensors**: MEMS accelerometers, Gyroscopes

Based on the Type of Output

- **Analog Sensors**: Thermocouples, Potentiometers, LDRs
- **Digital Sensors**: Rotary encoders, Digital temperature sensors (DHT11)

Based on the Sensing Principle

- **Electromagnetic Sensors**: Hall effect sensors, Inductive sensors
- **Capacitive Sensors**: Capacitive touch sensors, Humidity sensors
- **Resistive Sensors**: LDR, Thermistors
- **Piezoelectric Sensors**: Vibration sensors, Microphones
- **Optical Sensors**: Infrared sensors, Laser sensors

Based on the Power Requirement

- **Active Sensors** (Require external power): Ultrasonic sensors, IR sensors
- **Passive Sensors** (Self-powered, detect changes in environment): Thermocouples, LDRs

Based on the Applications

- **Industrial Sensors**: Pressure sensors, Proximity sensors
- **Automotive Sensors**: Oxygen sensors, RPM sensors
- **Medical Sensors**: ECG sensors, Pulse oximeters
- **Environmental Sensors**: Air quality sensors, CO_2 sensors
- Home Appliance Sensors:

Based on the Applications

- **Industrial Sensors:** Pressure sensors, Proximity sensors
- **Automotive Sensors:** Oxygen sensors, RPM sensors
- **Medical Sensors:** ECG sensors, Pulse oximeters
- **Environmental Sensors:** Air quality sensors, CO2 sensors
- **Home Appliance Sensors**
  - **Temperature Sensors**: Used in refrigerators, air conditioners, ovens
  - **Proximity Sensors**: Found in automatic doors, smart lighting
  - **Touch Sensors**: Capacitive touch panels in induction cooktops and microwaves
  - **Gas Sensors**: LPG leak detectors in gas stoves
- **Consumer Sensors**
  - **Motion Sensors:** Accelerometers in smartphones, smartwatches
  - **Biometric Sensors:** Fingerprint scanners, Heart rate sensors in wearables
  - **Optical Sensors:** Proximity sensors in smartphones, Ambient light sensors for screen brightness

Automotive Sensors

Automotive Sensors are crucial components in modern vehicles, playing a vital role in enhancing safety, performance and efficiency.

- Oxygen (O_2) Sensor
  - Function: Measures the oxygen level in exhaust gases to optimize fuel-air mixture.
  - Working: Uses a zirconia or titanium dioxide element to generate a voltage signal based on oxygen concentration. The ECU adjusts fuel injection accordingly.
- Mass Air Flow (MAF) Sensor
  - Function: Measures the amount of air entering the engine for proper fuel injection.
  - Working: Uses a heated wire or film. As air passes over it, the cooling effect changes resistance, which the sensor converts into a signal for the ECU.

- **Manifold Absolute Pressure (MAP) Sensor**
  - **Function:** Measures air pressure inside the intake manifold to adjust fuel mixture and ignition timing.
  - **Working:** Uses a diaphragm that flexes based on pressure changes, altering voltage output to the ECU.
- **Throttle Position Sensor (TPS)**
  - **Function:** Detects the position of the throttle valve to control acceleration and fuel injection.
  - **Working:** A potentiometer attached to the throttle shaft changes resistance as the throttle opens and closes.
- **Crankshaft Position Sensor**
  - **Function:** Monitors the crankshaft's rotation speed and position to control ignition timing and fuel injection.
  - **Working:** Uses a Hall effect or magnetic sensor to detect teeth on a rotating reluctor ring.

- **Camshaft Position Sensor**
  - **Function**: Monitors the camshaft's position to synchronize fuel injection and valve timing.
  - **Working**: Similar to the crankshaft sensor, it detects a rotating target using a magnetic or Hall effect sensor.
- **Wheel Speed Sensor (ABS Sensor)**
  - **Function**: Measures the rotational speed of each wheel for ABS and traction control.
  - **Working**: Uses a Hall effect or inductive sensor to detect the movement of a toothed wheel or magnetized ring.
- **Airbag Sensor**
  - **Function**: Detects a collision and triggers airbag deployment.
  - **Working**: Uses an accelerometer to measure sudden deceleration, sending a signal to deploy airbags.

- **Parking & Proximity Sensors**
  - **Function**: Detects obstacles around the vehicle for parking assistance.
  - **Working**: Uses ultrasonic waves that reflect off obstacles; the time delay is used to calculate distance.
- **Radar & LiDAR Sensors (For Adaptive Cruise Control & Collision Avoidance)**
  - **Function**: Detects vehicles and objects for adaptive cruise control and emergency braking.
  - **Working**: Radar uses radio waves, and LiDAR uses laser pulses to measure distances and object speed.
- **Fuel Level Sensor**
  - **Function**: Measures the amount of fuel in the tank.
  - **Working**: Uses a float attached to a variable resistor, which changes resistance as fuel level changes.

Summary Table:

Feature	Thermocouples	RTDs	Thermistors
Principle	Seebeck effect	Resistance change in metals	Resistance change in semiconductors
Temperature Range	-200°C to 2000°C+	-200°C to 850°C	-50°C to 150°C (up to 300°C)
Accuracy	±1°C to ±2°C	±0.1°C to ±0.5°C	±0.1°C to ±0.5°C
Sensitivity	Low	Moderate	High
Response Time	Fast	Slower	Fast
Cost	Low	High	Low to moderate
Linearity	Nonlinear	Linear	Nonlinear
Applications	High-temperature industrial	Precise measurements	Consumer electronics, automotive

Each sensor type has its strengths and weaknesses, so the choice depends on the specific application requirements, such as temperature range, accuracy, and cost.

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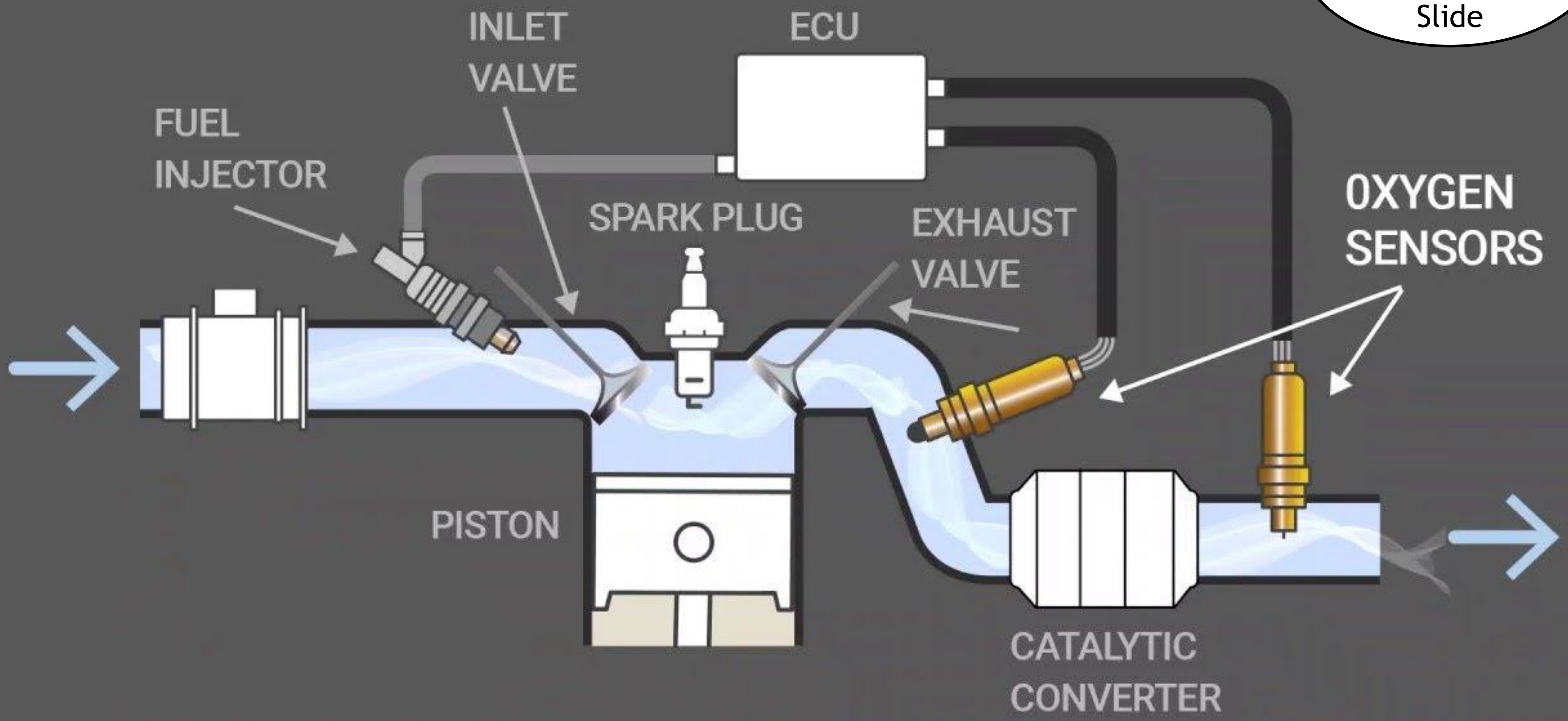
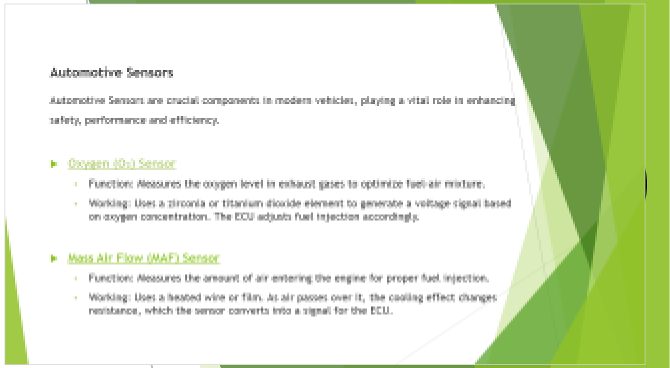
How Oxygen Sensors work

Return to Previous Slide

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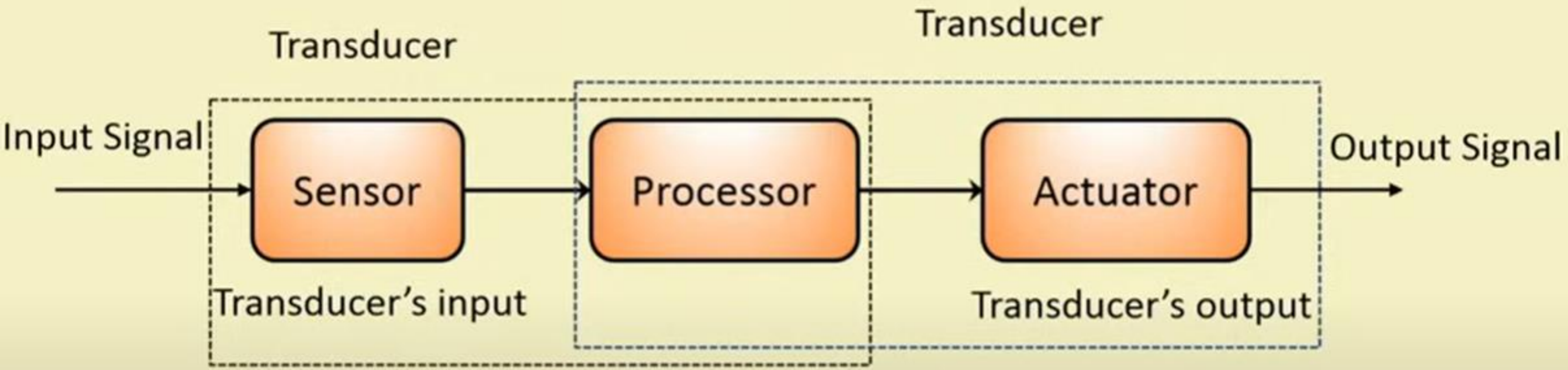
Transducer


Transducer
Transducer
Input Signal
Sensor
Processor
Actuator
Output Signal
Transducer's input
Transducer's output

Transducer (Contd.)

- Transducer:
  - Converts a signal from one physical form to another physical form
  - Physical form: thermal, electric, mechanical, magnetic, chemical, and optical
  - <u>Energy converter</u>
  - Example:
    - Microphone : Converts sound to electrical signal
    - Speaker : Converts electrical signal to sound
    - Antenna : Converts electromagnetic energy into electricity and vice versa
    - Strain gauge : Converts strain to electrical

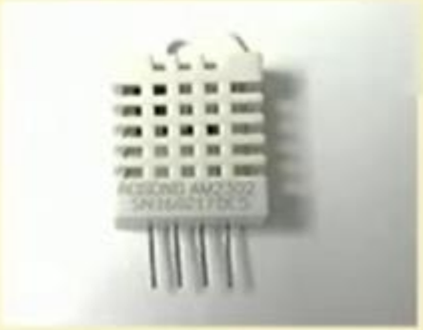
Definition of Sensor

- The characteristic of any device or material to detect the presence of a particular physical quantity
- The output of sensor is signal, which is converted to human readable form

Sensor

- Performs some function of input by sensing or feeling the physical changes in the characteristic of a system in response to <u>stimuli</u>
- Input: Physical parameter or stimuli
  - Example: Temperature, light, gas, pressure, and sound
- Output: Response to stimuli

Sensor (Contd.)

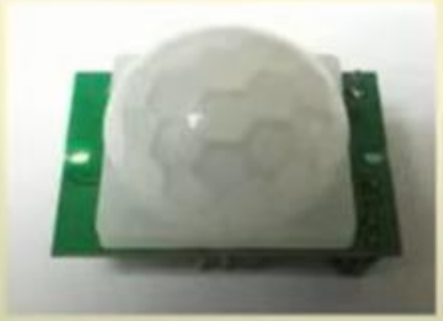


Temperature and Humidity sensor – DH22

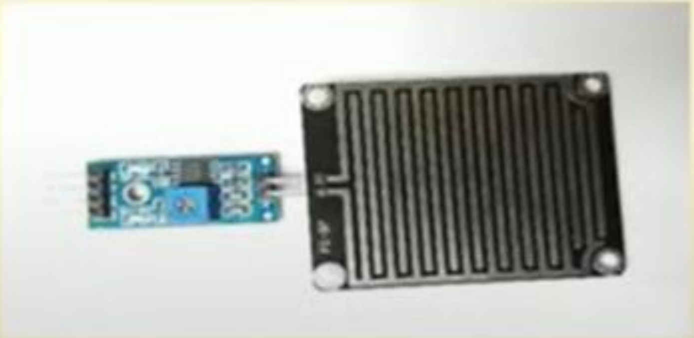
Gas (LPG, CH4, and CO) detector sensor - MQ-5

Ultrasonic sensor - HC-SR04

CMOS Camera



PIR sensor



Rain detector sensor

Fire detector sensor

Sensor Characteristics

- Static characteristics
  - After steady state condition, how the output of a sensor change in response to an input change
- Dynamic characteristics
  - The properties of the system's transient response to an input

Static characteristics

- Accuracy
  - Represents the correctness of the output compared to a superior system
  - The different between the standard and the measured value
- Range
  - Gives the highest and the lowest value of the physical quantity within which the sensor can actually sense
  - Beyond this value there is no sensing or no kind of response

Static Characteristics (Contd.)

- Resolution
  - Provides the smallest change in the input that a sensor is capable of sensing
  - Resolution is an important specification towards selection of sensors.
  - Higher the resolution better the precision
- Errors
  - The difference between the standard value and the value produced by sensor

Static Characteristics (Contd.)

- Sensitivity
  - Sensitivity indicates ratio of <u>incremental change in the response of the system with respect to incremental change in input parameter</u>.
  - It can be found from slope of output characteristic curve of a sensor
- Linearity
  - The deviation of sensor value curve from a particular <u>straight line</u>

Sensor Characteristics (Contd.)

- Drift
  - The difference in the measurements of sensor from a specific reading when kept at that value for a long period of time
- Repeatability
  - The deviation between measurements in a sequence under same conditions

Dynamic Characteristics

How well a sensor responds to changes in its input

- Zero order system
  - Output shows a response to the input signal with no delay
  - Does not include energy-storing elements
  - Example: Potentiometer measures linear and rotary displacements

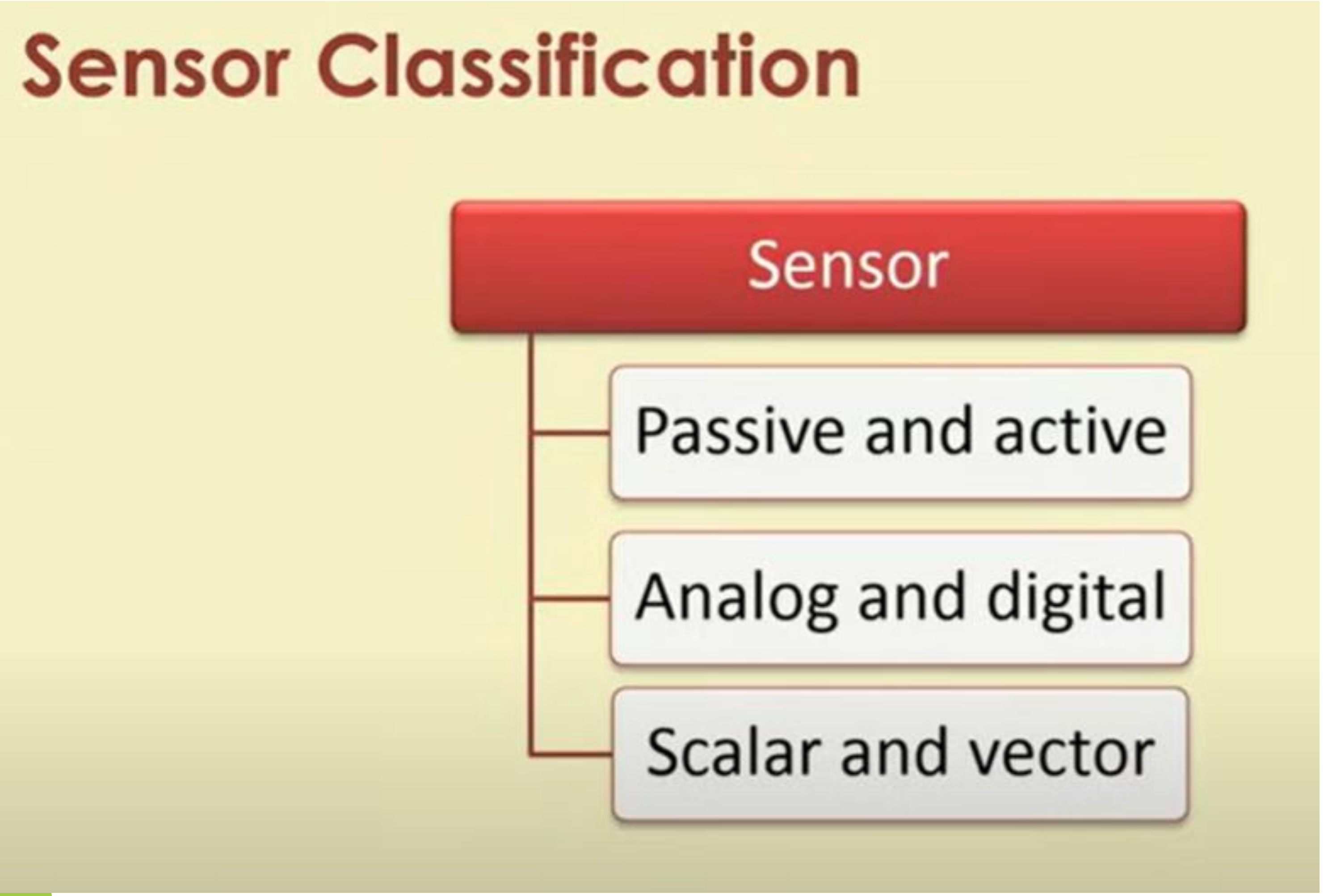
Dynamic Characteristics

How well a sensor responds to changes in its input

- Zero order system
  - Output shows a response to the input signal with no delay
  - Does not include energy-storing elements
  - Example: Potentiometer measures linear and rotary displacements

Dynamic Characteristics (Contd.)

- First order system
  - When the output approaches its final value gradually
  - Consists of an energy storage and dissipation element
- Second order system
  - Complex output response
  - The output response of sensor oscillates before steady state


Sensor Classification
Sensor
Passive and active
Analog and digital
Scalar and vector

Passive Sensor

- Cannot independently sense the input
- Example: Accelerometer, soil moisture, water-level, and temperature sensors

Active Sensor

- Independently sense the input
- Example: Radar, sounder, and laser altimeter sensors

Analog Sensor

- The response or output of the sensor is some <u>continuous function</u> of its input parameter
  - Example: Temperature sensor, LDR, analog pressure sensor, and Analog Hall effect/Magnetic Sensor
    - A LDR shows continuous variation in its resistance as a function of intensity of light falling on it

Digital Sensor

- Responses in binary nature
- Designs to overcome the disadvantages of analog sensors
- Along with the analog sensor it also comprises of extra electronics for bit conversion
- Example: Passive infrared (PIR) sensor and digital temperature sensor (DS1620)

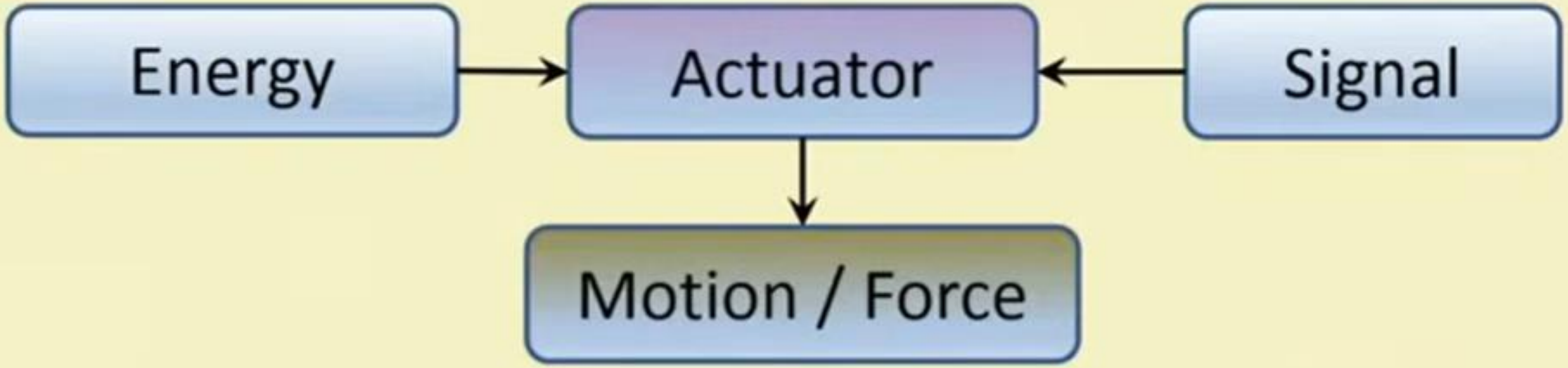
Scalar Sensor

- Detects the input parameter only based on its magnitude
- The response of the sensor is a function of magnitude of the input parameter
- Not affected by the direction of the input parameter
- Example: Temperature, gas, strain, color, and smoke sensors

Vector Sensor

- The response of the sensor depends on the magnitude of the direction and orientation of input parameter
- Example : Accelerometer, gyroscope, magnetic field, and motion detector sensors

Actuator



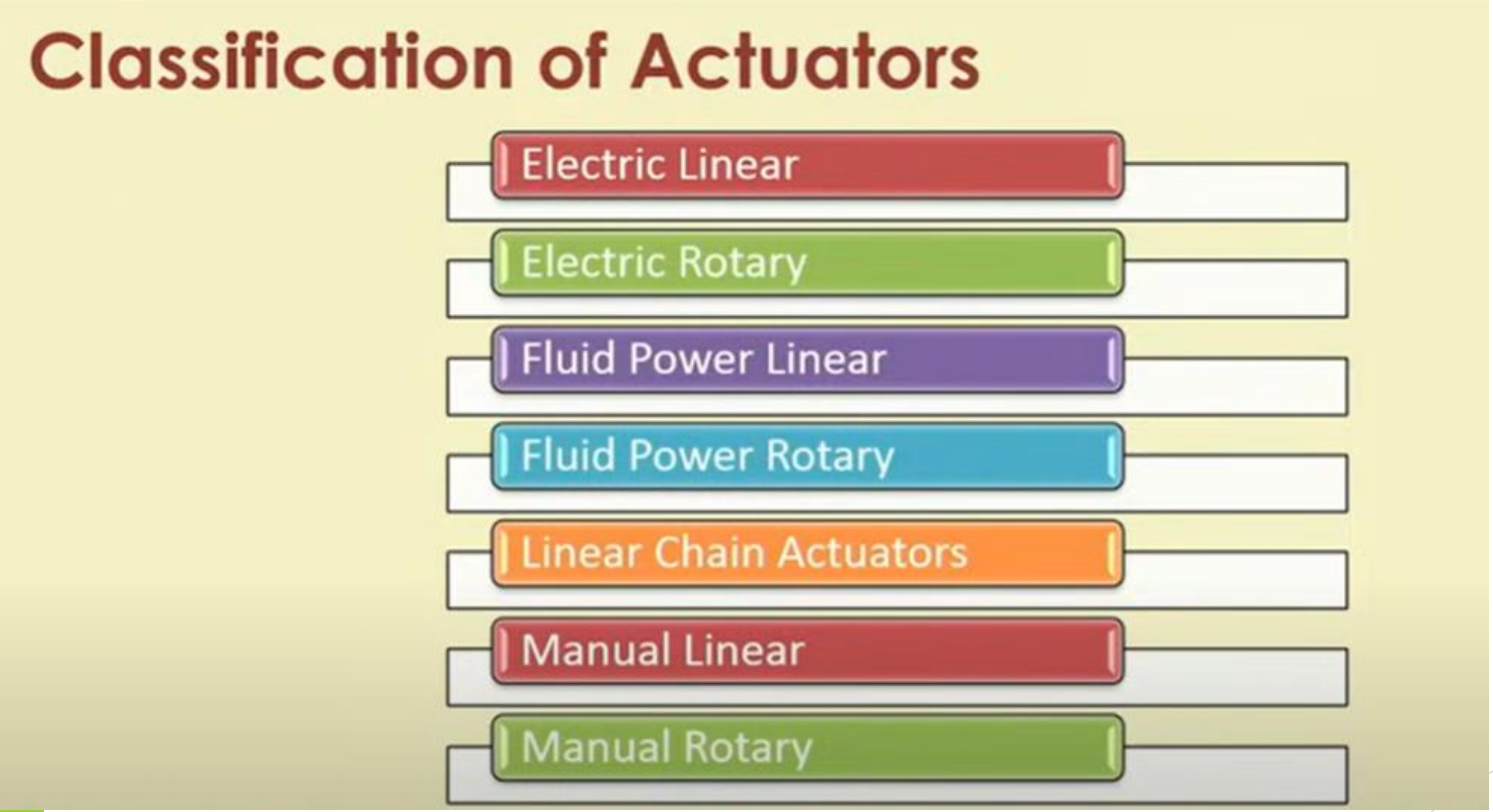
- An actuator is part of the system that deals with the control action required (mechanical action)
- Mechanical or electro-mechanical devices

Actuator (Contd.)

- A control signal is input to an actuator and an energy source is necessary for its operation
- Available in both micro and macro scales
- Example: Electric motor, solenoid, hard drive stepper motor, comb drive, hydraulic cylinder, piezoelectric actuator, and pneumatic actuator

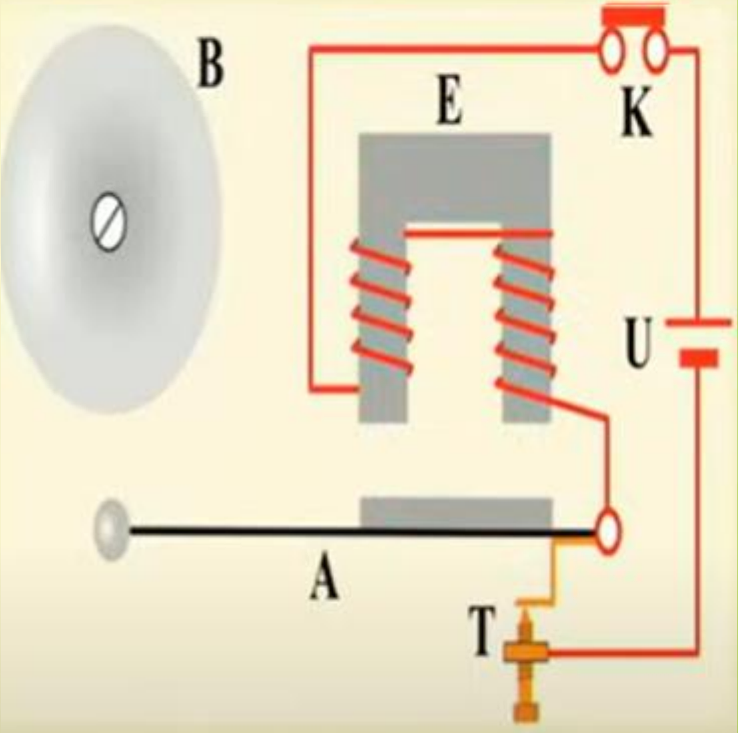
DC Motor

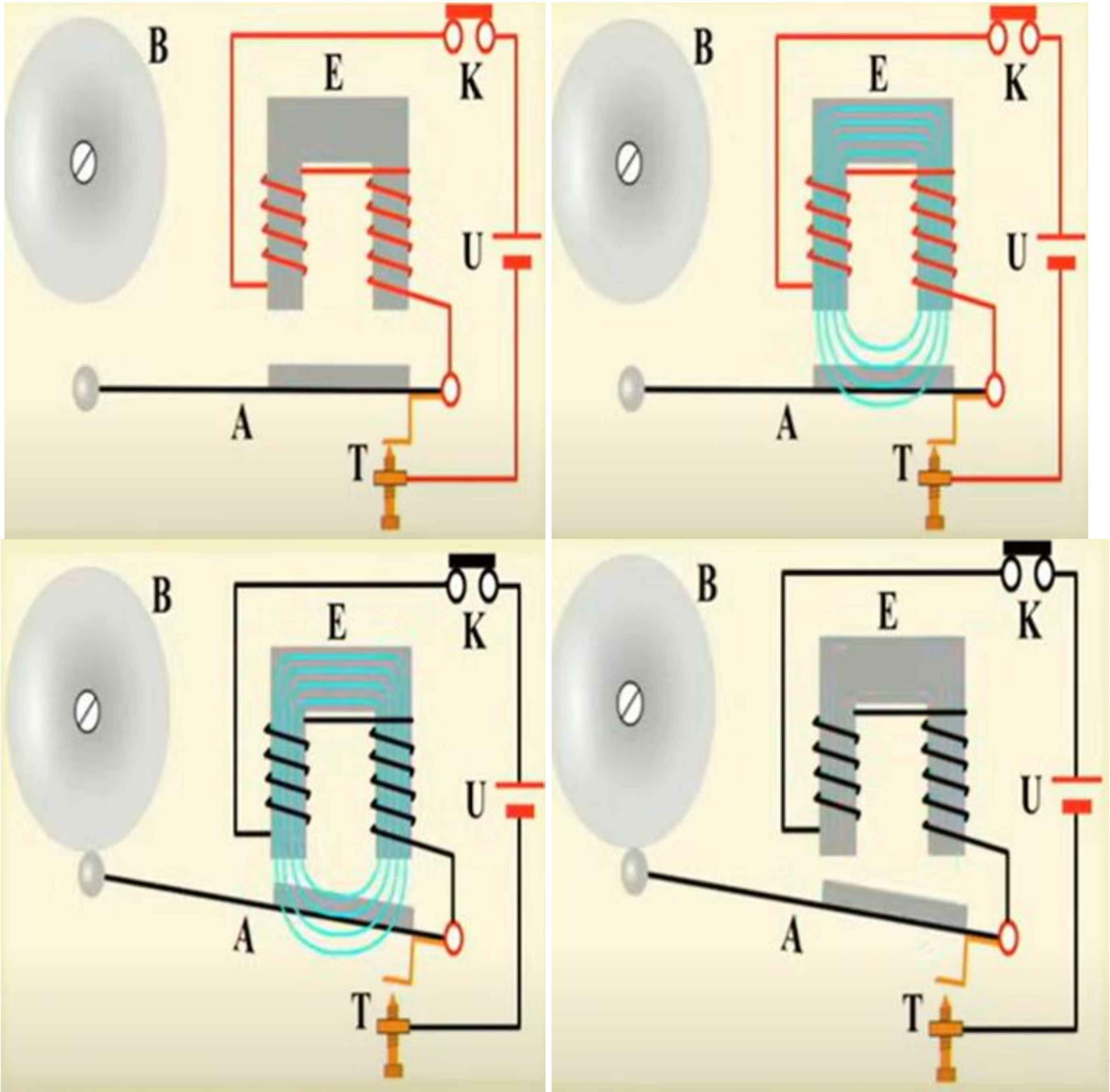
Relay


Classification of Actuators
Electric Linear
Electric Rotary
Fluid Power Linear
Fluid Power Rotary
Linear Chain Actuators
Manual Linear
Manual Rotary

Electric Linear Actuator

- Powered by electrical signal
- Mechanical device containing linear guides, motors, and drive mechanisms
- Converts electrical energy into linear displacement
- Used in automation applications including electrical bell, opening and closing dampers, locking doors, and braking machine motions

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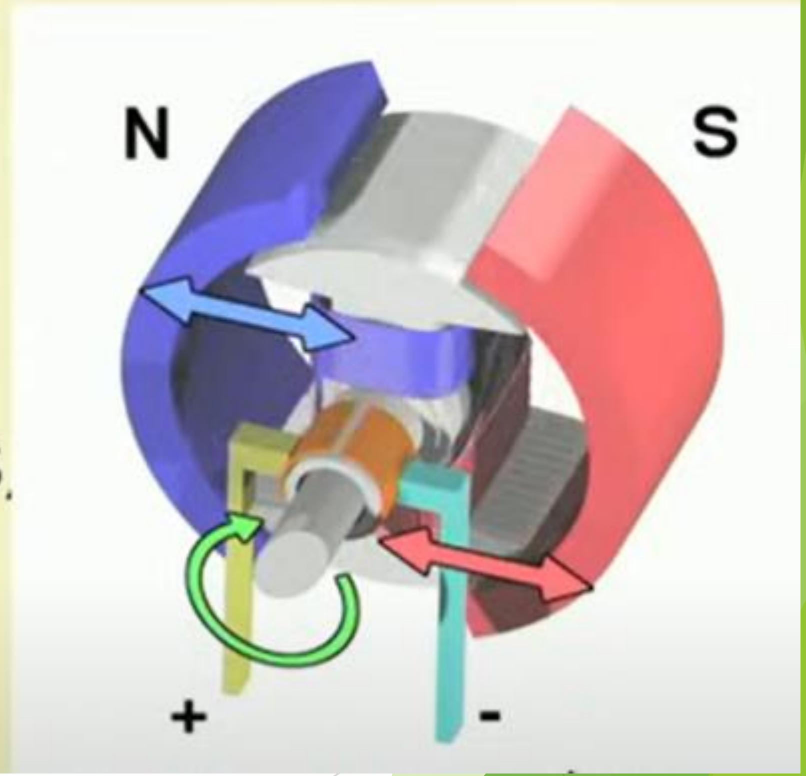
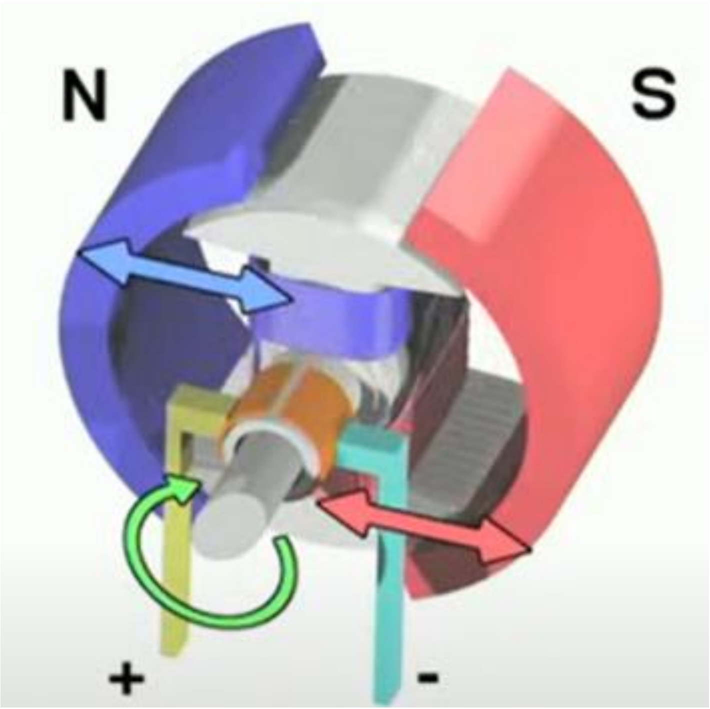
Electric Rotary Actuator

- Powered by electrical signal
- Converts <u>electrical energy</u> into <u>rotational motion</u>
- Applications including quarter-turn valves, windows, and robotics

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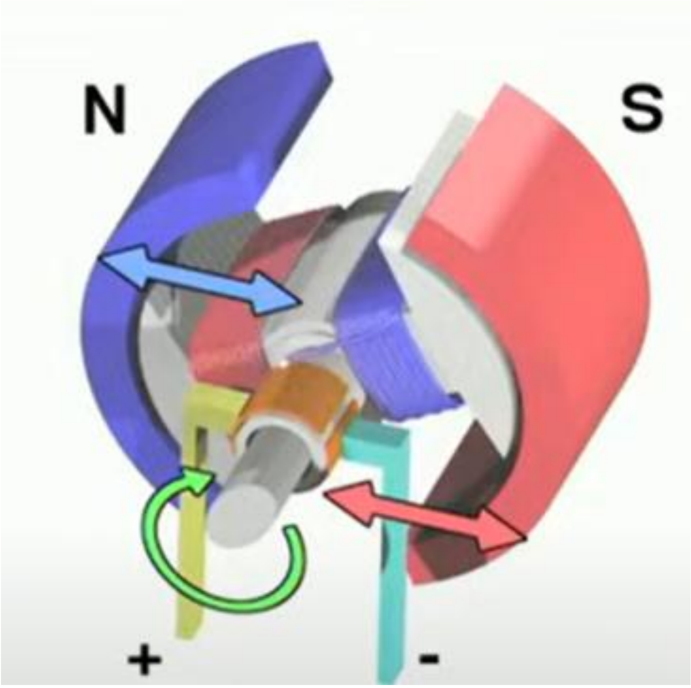
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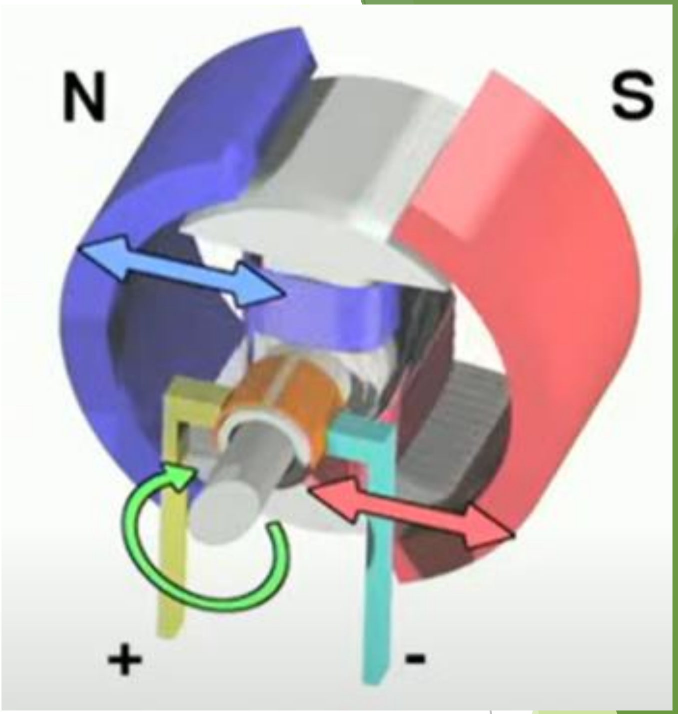
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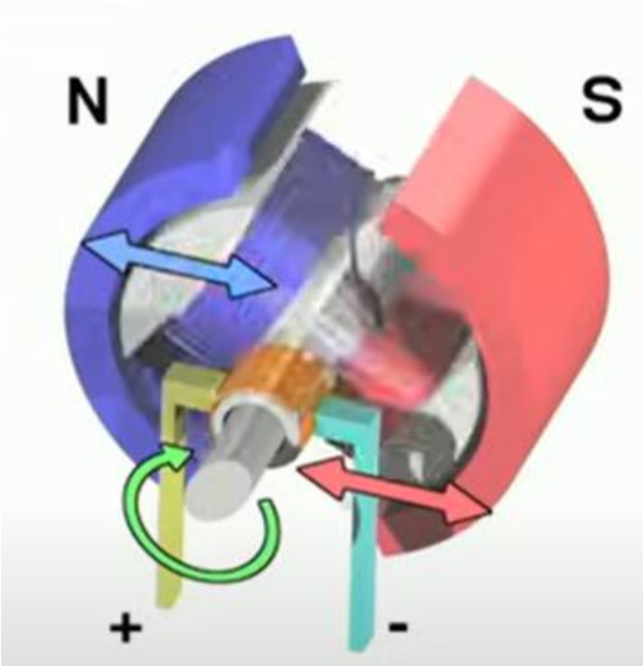
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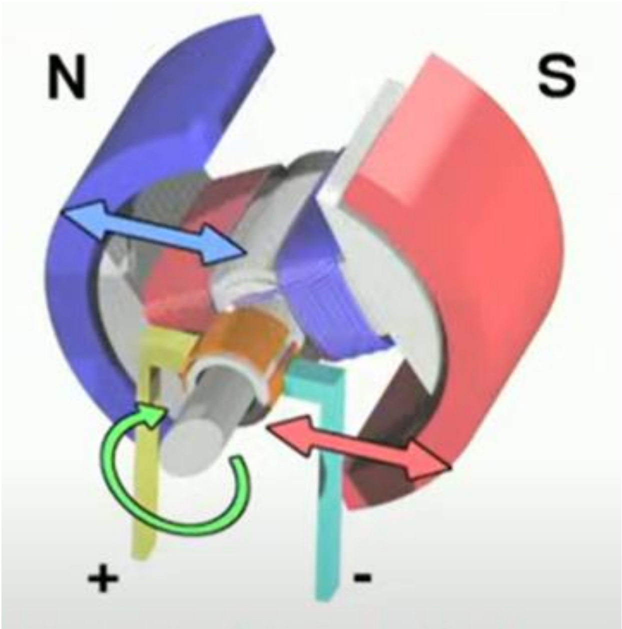
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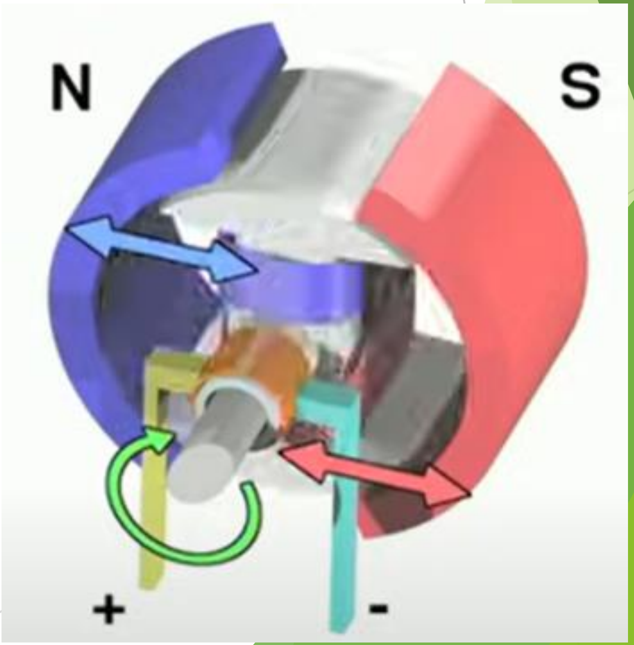
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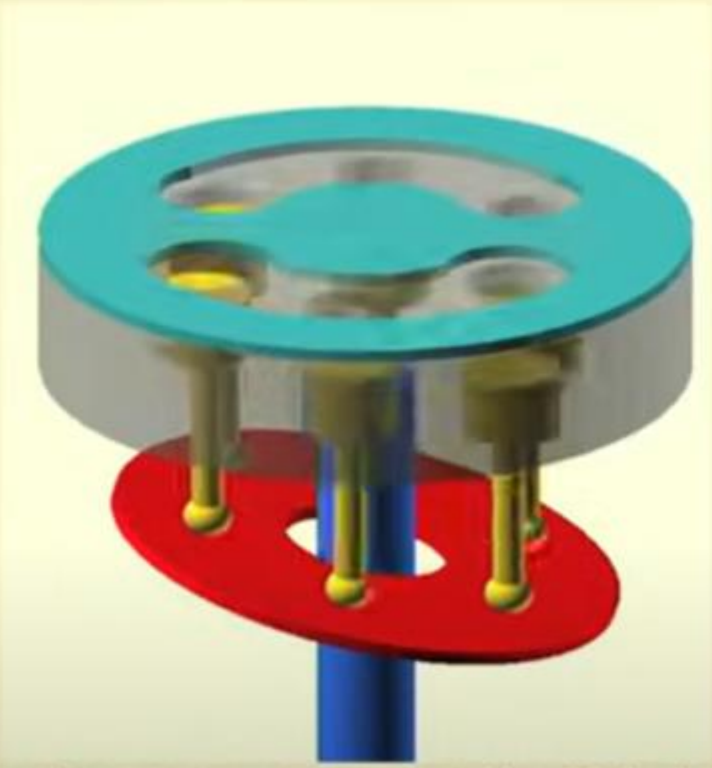
Fluid Power Linear Actuator

- Powered by hydraulic fluid, gas, or differential air pressure
- Mechanical devices have cylinder and piston mechanisms
- Produces linear displacement
- Primarily used in automation applications including clamping and welding

Fluid Power Rotary Actuator

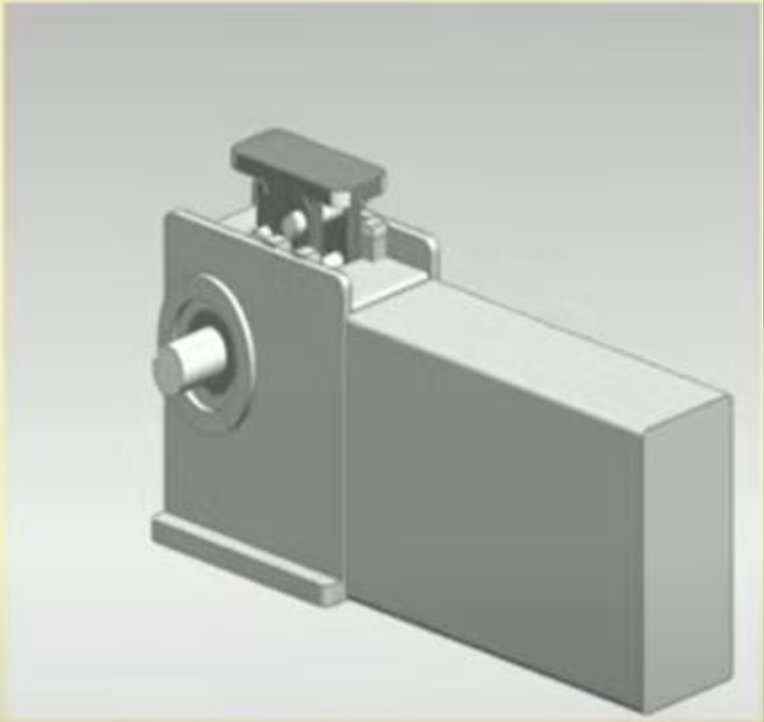
- Powered by fluid, gas, or differential air pressure
- Consisting of gearing, and cylinder and piston mechanisms
- Converts hydraulic fluid, gas, or differential air pressure into rotational motion
- Primarily applications of this actuator are opening and closing dampers, doors, and clamping

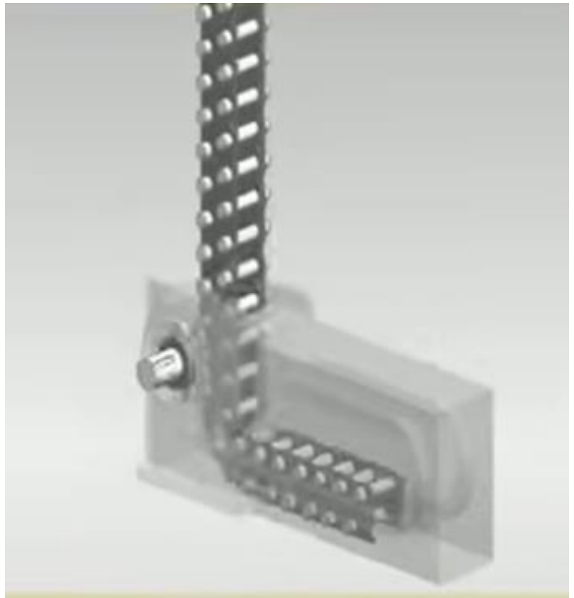
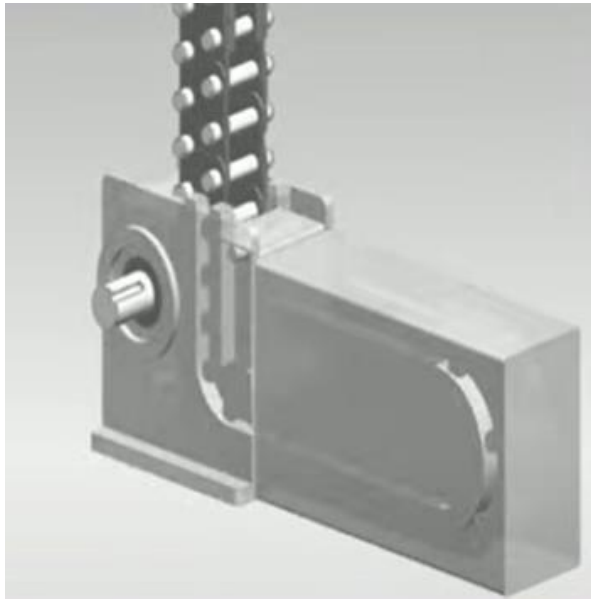


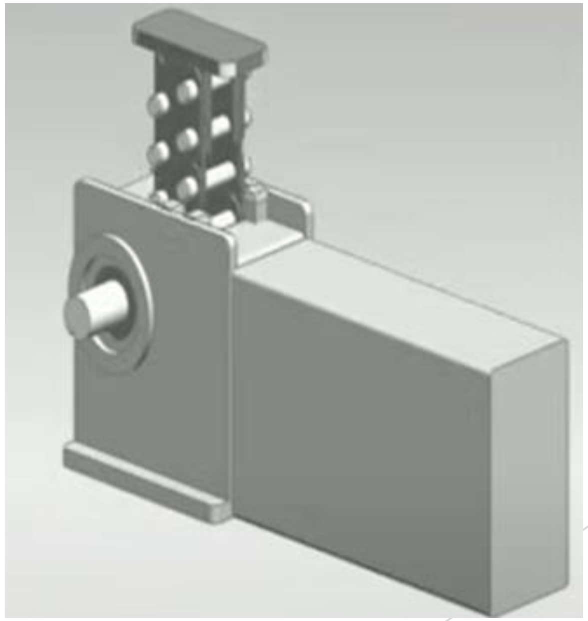
Source: "Axial piston pump", MichaelFrey / Wikimedia Commons / CC-BY-SA-4.0 International/. Published date: 11 August 2017, Online: https://commons.wikimedia.org/wiki/File:Axialkolbenpumpe_-_einfache_Animation.gif

Linear Chain Actuator

- Mechanical devices containing sprockets and sections of chain
- Provides linear motion by the free ends of the specially designed chains
- Primarily used in motion control applications





Manual Linear Actuator

- Provides linear displacement through the translation of manually rotated screws or gears
- Consists of gearboxes, and hand operated knobs or wheels
- Primarily used for manipulating tools and workpieces

Manual Rotary Actuator

- Provides rotary output through the translation of manually rotated screws, levers, or gears
- Consists of hand operated knobs, levers, handwheels, and gearboxes
- Primarily used for the operation of valves

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