Module 3

Actuator Performance and Selection

Electrical actuating systems: solid-state switches, solenoids and electric motors: DC motor, stepper motor, and Inertial measurement unit, Mechanical actuating systems: types of motion, kinematic chains, cams and gears, Pneumatic and hydraulic actuating systems: diaphragms, bellows and control valves.

Introduction

The electrical systems used as actuators for control.

1. Switching devices: Mechanical switches to control signal electrical device (e.g. Motor, heater etc.) e.g. relays, and solid-state switches, e.g. diodes, thyristors, and transistors.

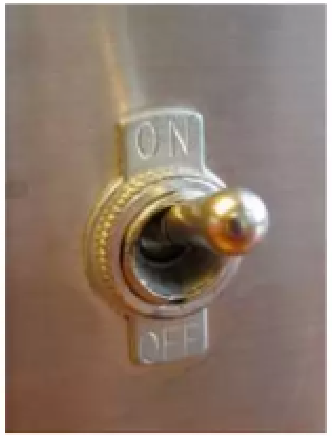
2. Solenoid-type devices: Current through a solenoid is used to actuate / operate hydraulic / pneumatic valve to control the flow.

3. Drive systems: D.C. and A.C. motors. (current through motor is used to produce rotation).

Mechanical Switches

- Elements, used as sensors to give input to systems.
- Interrupting the current or diverting it from one conductor to another.

E.g.: Switch on electric motors, heating elements.



Toggle Switch

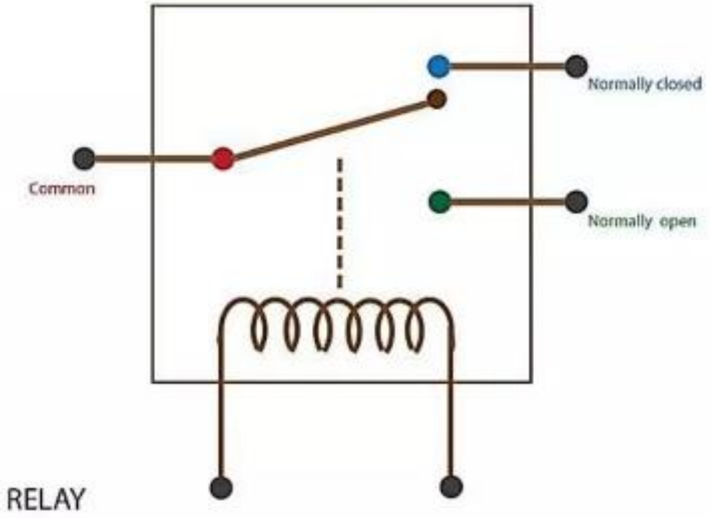
The electrical relay is an example of a mechanical switch used in control systems as an actuator.

Relays

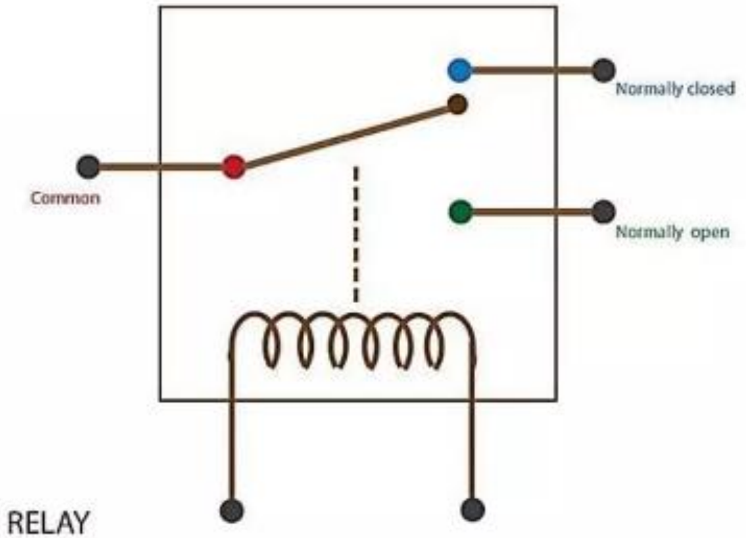
- Electrically operated switches.
- Consists of a set of input terminals for a single or multiple control signals, and a set of contact terminals.
- The switch may have any number of contacts in multiple contact forms, to make contacts or break contacts.
- Used to control a circuit by an independent low-power signal, or several circuits must be controlled by one signal
- Traditional relay uses an electromagnet to close or open the contacts.

Relays

- A relay has electrical and mechanical components, hence it is an electromechanical device.
- It consists of three contact terminal known as
  - common (COM),
  - normally closed (NC)
  - normally opened(NO).
- In order to control the electric circuit, the relays close and open these contacts.
- An electromechanical relay consists of three terminals namely common (COM), normally closed (NC) and normally opened (NO) contacts.
- These can either get opened or closed when the relay is in operation.

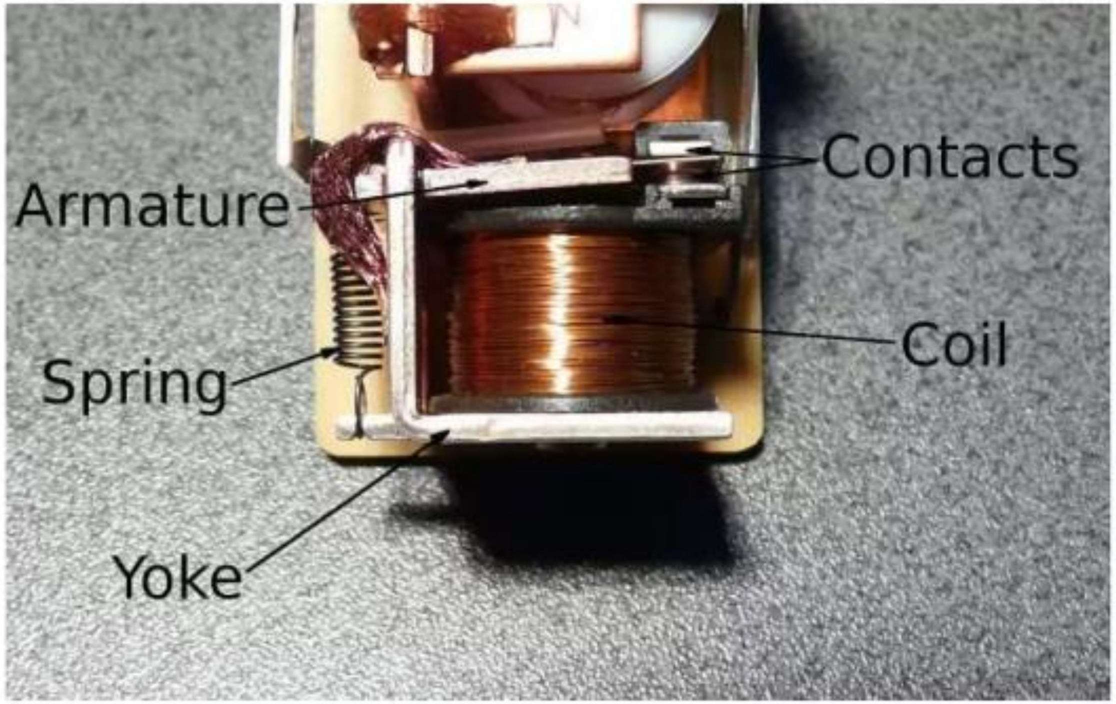


Relays

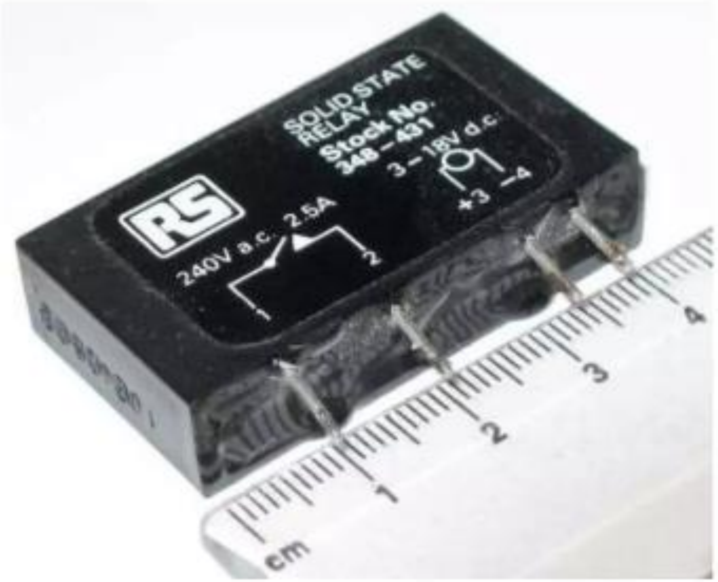


- Electromechanical relays can work on both AC and DC supply.
- Relays work on the principle of electromagnetic induction.
- One major differences is that the AC relays have special circuit arrangement to provide continuous magnetic field as in an AC relay, the demagnetization of coil happens each time it reaches the current zero position.

Relays



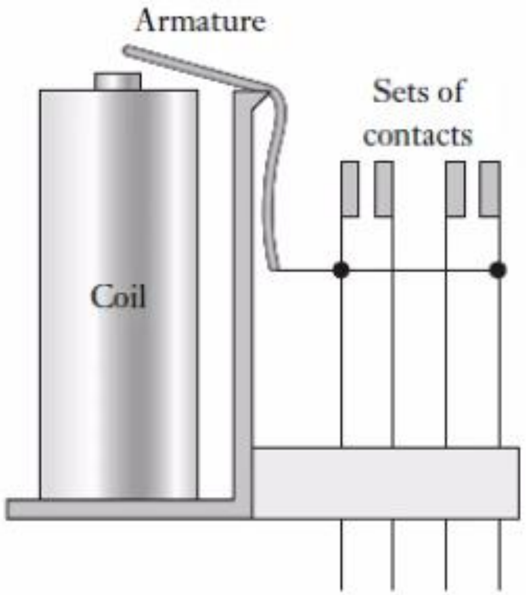
Traditional relay

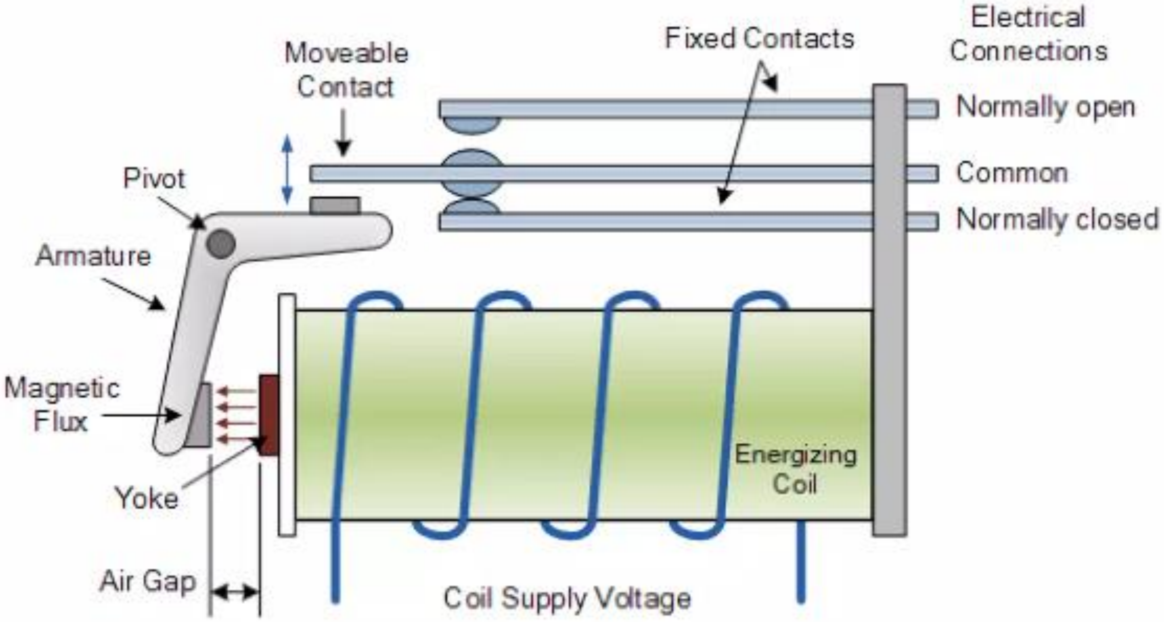


Solid state relay

Relays

- Changing a current in one electric circuit, switches a current on or off in another circuit.





Current through the solenoid relay produces magnetic field, which attracts the iron armature, moves the push rod.

- Closes the normally open (NO) switch contacts
- Opens the normally closed (NC) switch contacts.

Limitation of Relay

- Relays are inductances, generate a back voltage, when the energising current is switched off or when the input switches from a high to low signal, results in a damaging the circuit.

- To overcome this, a diode is connected across the relay.
- When the back e.m.f. occurs, the diode conducts and shorts it out, such a diode is termed a free-wheeling or flyback diode.

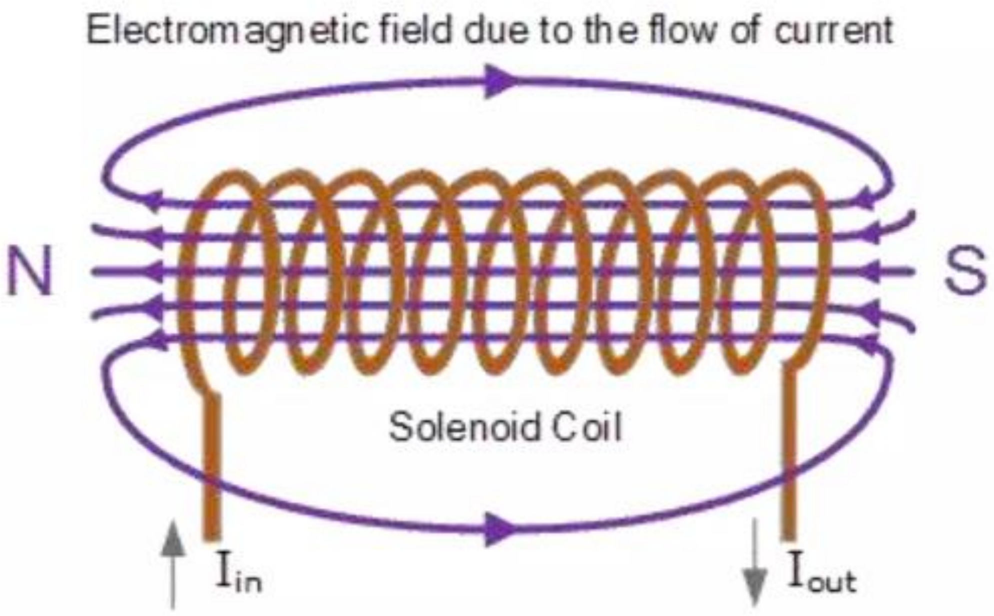
Applications / selection of Relay

Applications based on criterion like,

- Rating of contacts
- No. & type of contacts
- Voltage rating of contacts.
- Operating lifetime
- Coil voltage & current etc. so on.
- Used in power system networks for controlling purpose, automation purpose, and protection purpose.

Solenoids

Electromagnetic actuator that converts an electrical signal into a magnetic field



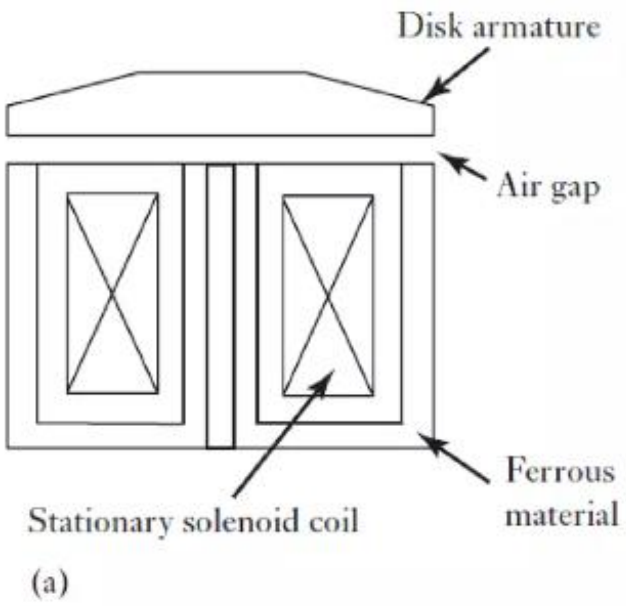
- Solenoids consist of a coil with an armature.
- When a current passes through it, armature is attracted to the coil and produces a magnetic field.
- When the current ceases, armature contracts a return spring, which then allows the armature to return to its original position.

Solenoids

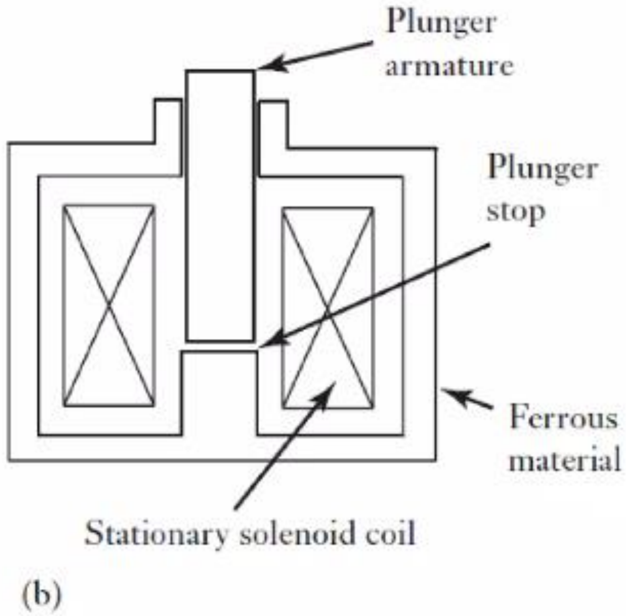
- The solenoids can be linear or rotary, on/off or variable positioning and are operated by D.C. or A.C.
- Used as electrically operated actuators for short stroke devices, up to 25 mm.

Solenoids

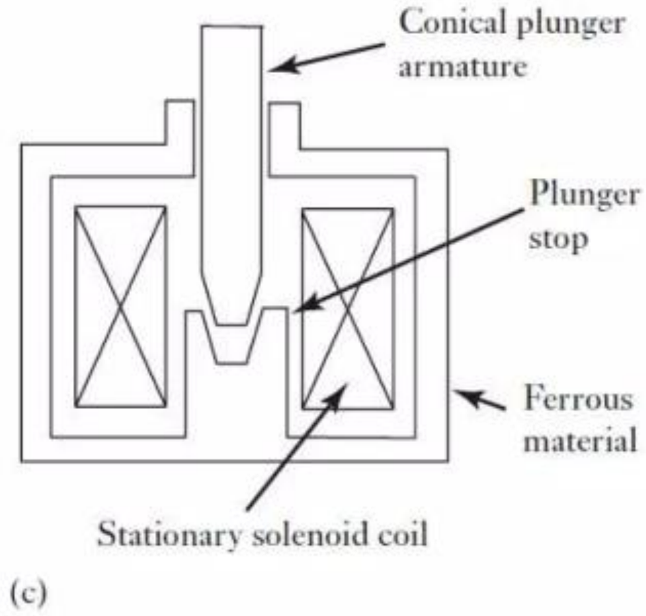
- The basic forms of linear solenoids with (a) disk, (b) plunger, (c) conical plunger, (d) ball forms of armature



(a) disk



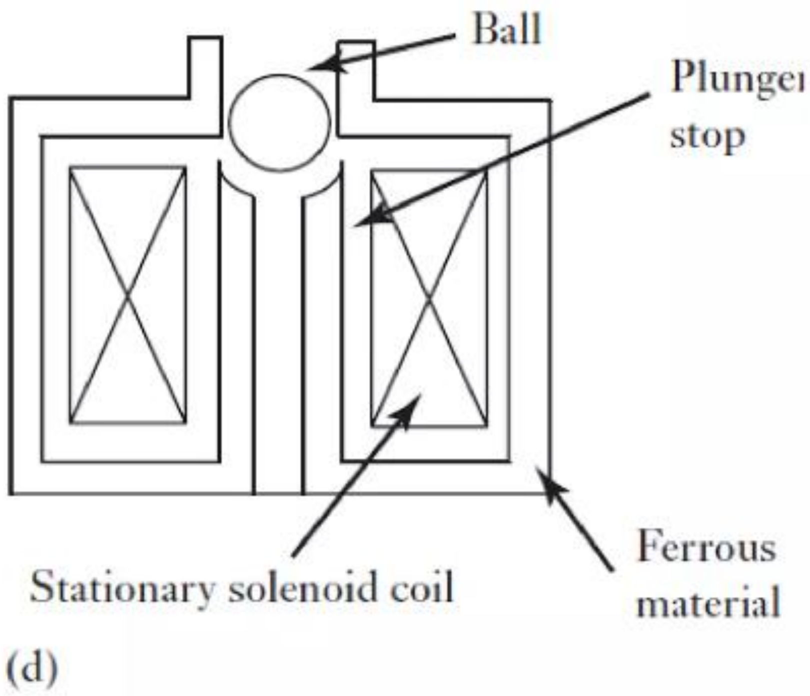
(b) plunger



(c) conical plunger

Solenoids

The basic forms of linear solenoids



(d) ball forms of armature

The form of the armature, the pole pieces and the central tube depends on the use for which the actuator is designed.

Solenoids

1. Disk armatures: Useful for small distances of travel and fast action are required.
2. Plunger armatures: Used for small distances of travel and fast action.
3. Conical armatures: Used for long-stroke applications

   e.g.: automotive door lock mechanism.

4. Ball armatures: Used with fluid control applications

   e.g.: air bag deployment

Electric motors

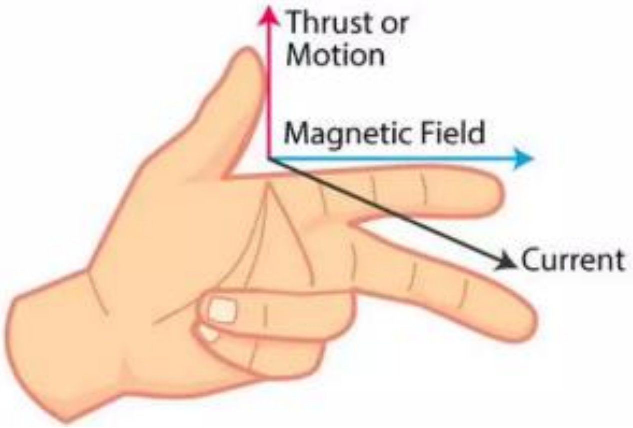
Electric motors, used as control element in positional and speed control systems.

Motors classification:

1. D. C Motors (brushless and brush type)
2. A.C. Motors

- In modern control systems D.C. motors are being used.

Fleming's Left Hand Rule is applicable to all electric motors.



Electric motors

Motors can be classified into two main categories:

1. D.C. motors
2. A.C. motors

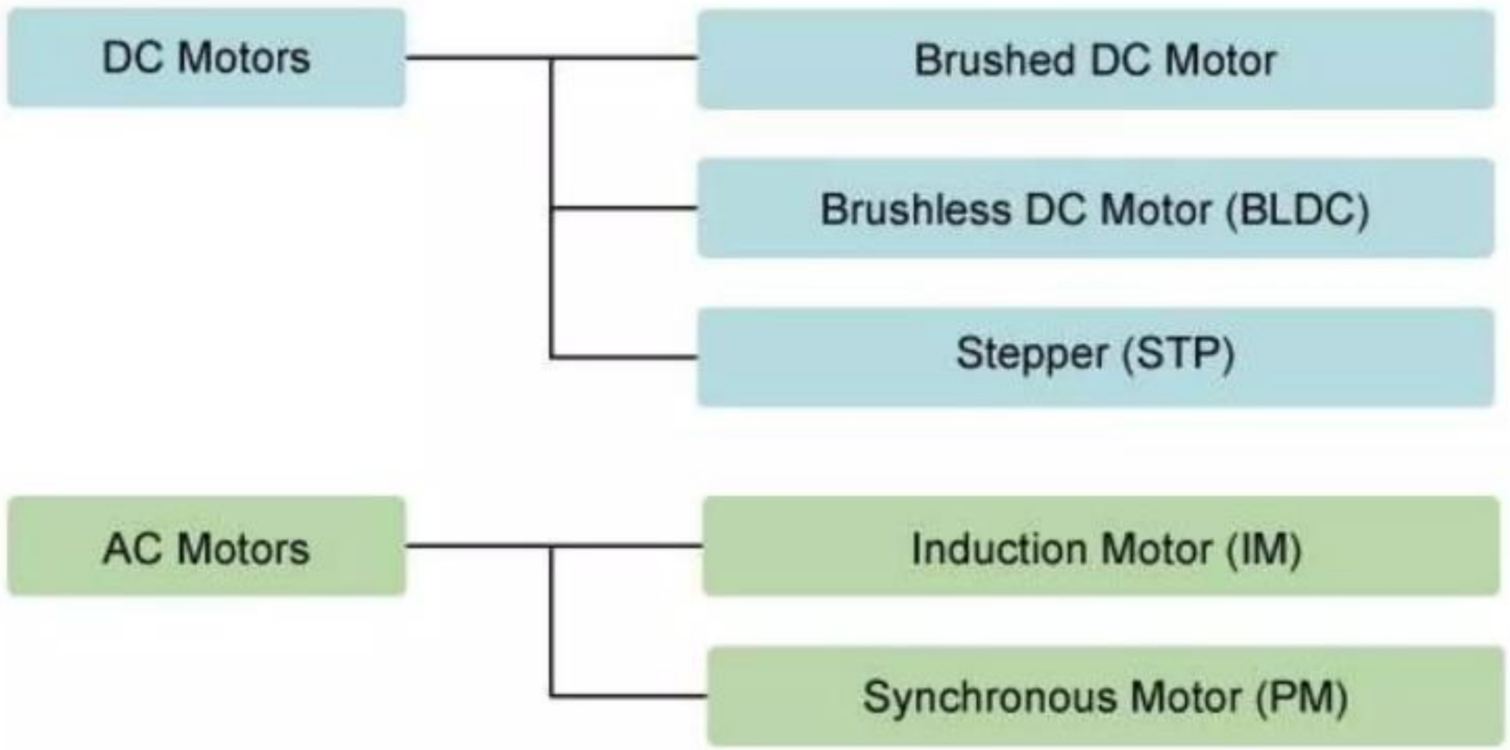
D.C. motors into two main groups; 1. Brush type and 2. Brushless type

- **Brush type:** Use brushes to make contact with a commutator ring assembly on the rotor to switch the current from one rotor winding to another.
- Brush type of motor, the rotor has the coil winding and the stator can be either a permanent magnet or an electromagnet.

- **Brushless type:** The arrangement is reversed in that the rotor is a permanent magnet and the stator has the coil winding.

Classification

Motors classification:



Direct Current (DC) Motors

Working Principle:

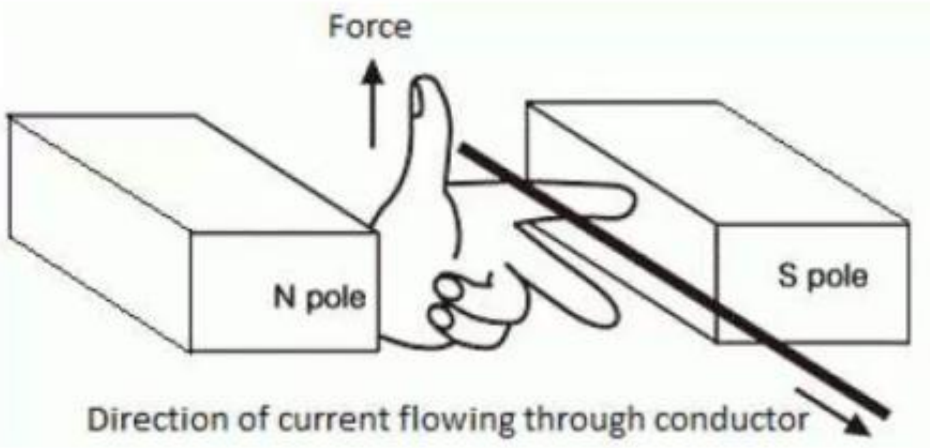
- When current carrying conductor is kept in a Magnetic field a mechanical force acts on the conductor, tends to rotate it in direction of force.
- The direction of force is given by Fleming's left hand rule and the magnitude of the force is given by equation;

$$F = BIL \qquad N \text{ (Newton)}$$

B= flux density, wb/m²

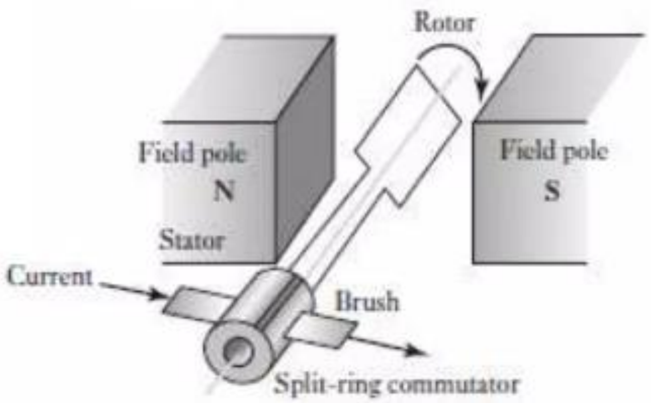
I= current, Ampere

L= length of conductor, meter

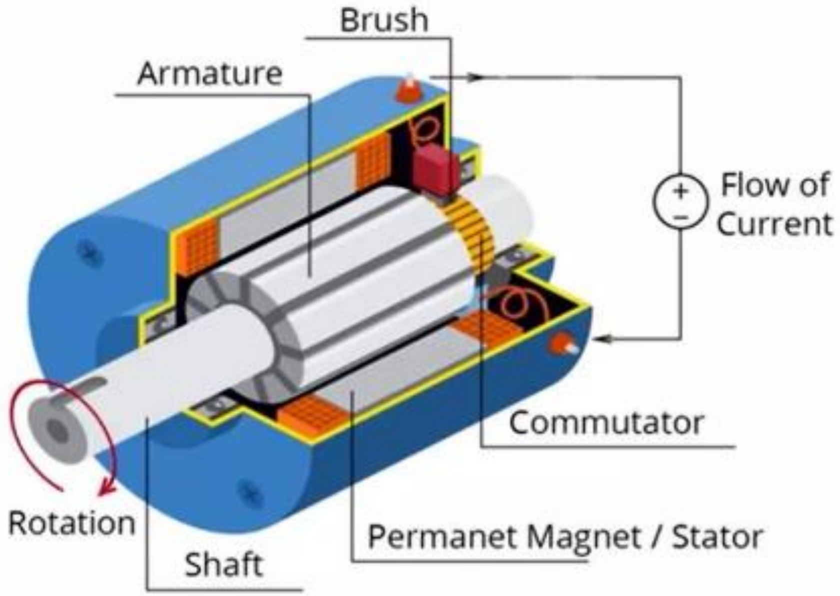


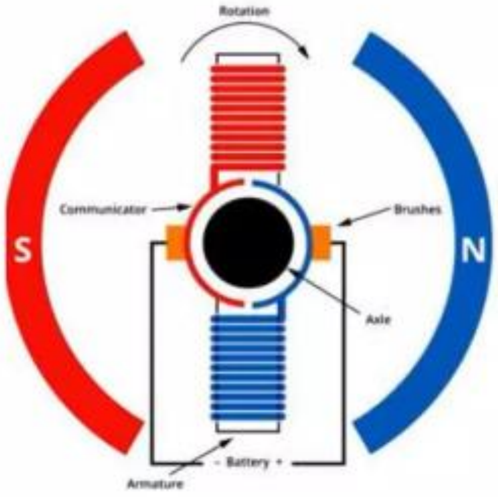
Direct current motors

Brush-type d.c. motor



A brush-type d.c. motor is a coil of wire, free to rotate (rotor), in the field of a permanent magnet (stator).

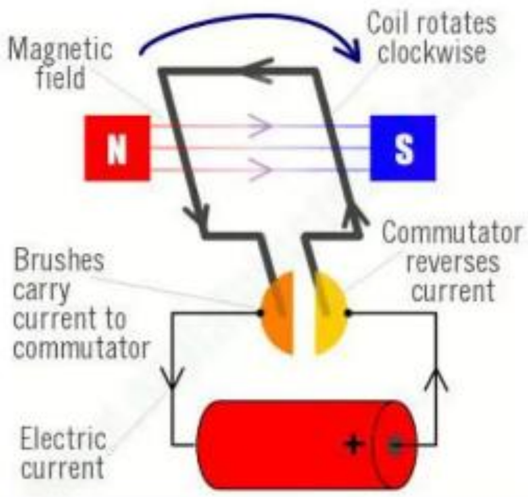


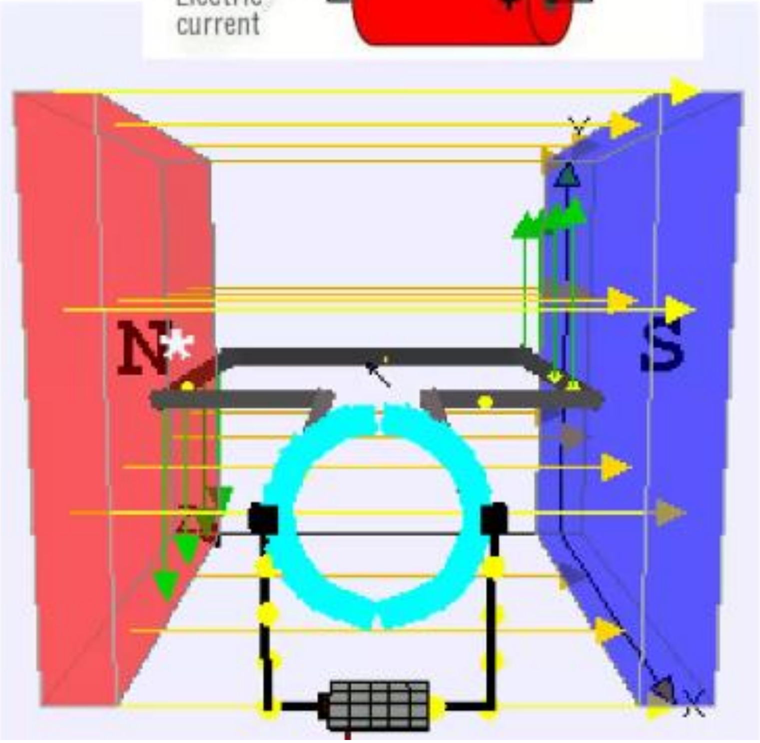


Brush-type d.c. motor

Direct current motors

- For the rotation to continue, when the coil passes through the vertical position the current direction through the coil has to be reversed.
- This is done by use of brushes making contact with a commutator.
- The commutator reverses the current in each coil as it moves between the field poles for the rotation to continue.
- The direction of rotation can be reversed by reversing either the armature current or the field current

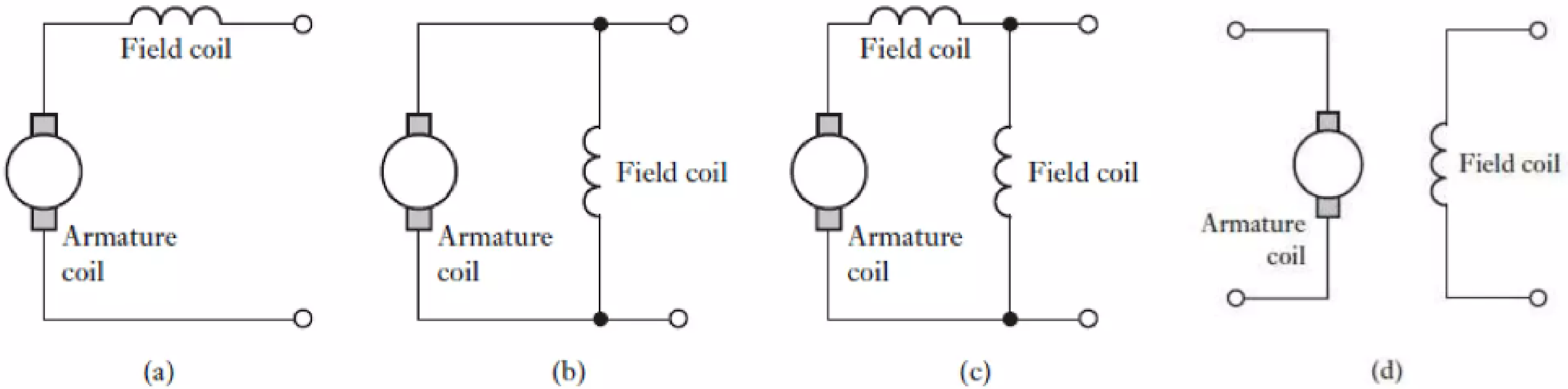




Classification

Direct current motors

- Direct current motors with field coils are classified as;



(a) Series (b) shunt (c) compound (d) separately wound

(a) Large starting torques are required.

(b) Low starting torque and constant speed.

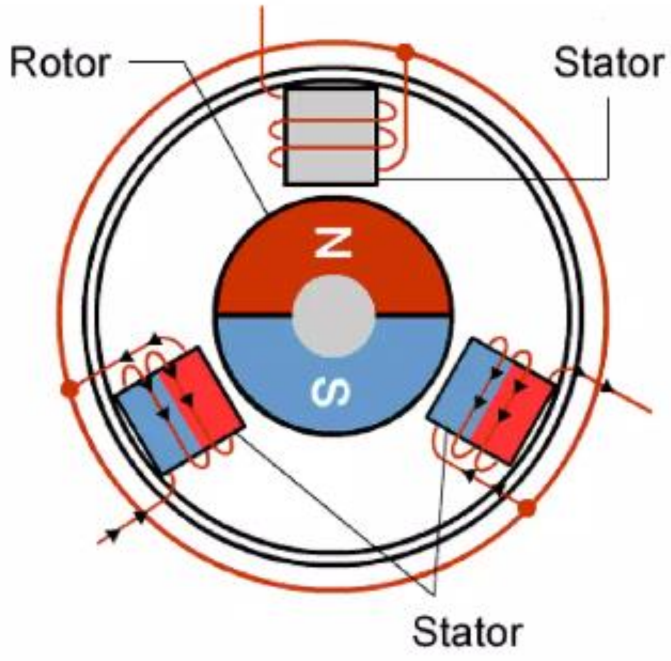
(c) High starting torque and good speed regulation.

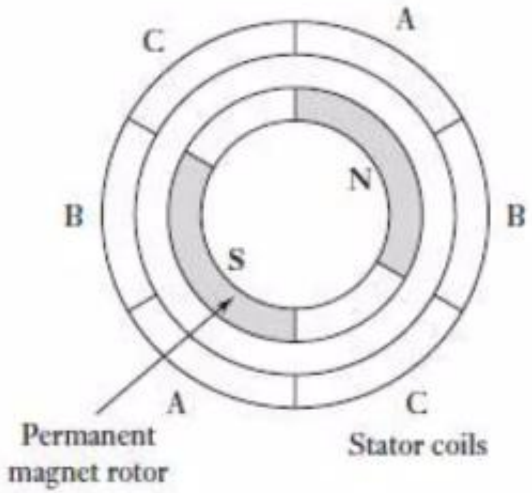
(d) Special case

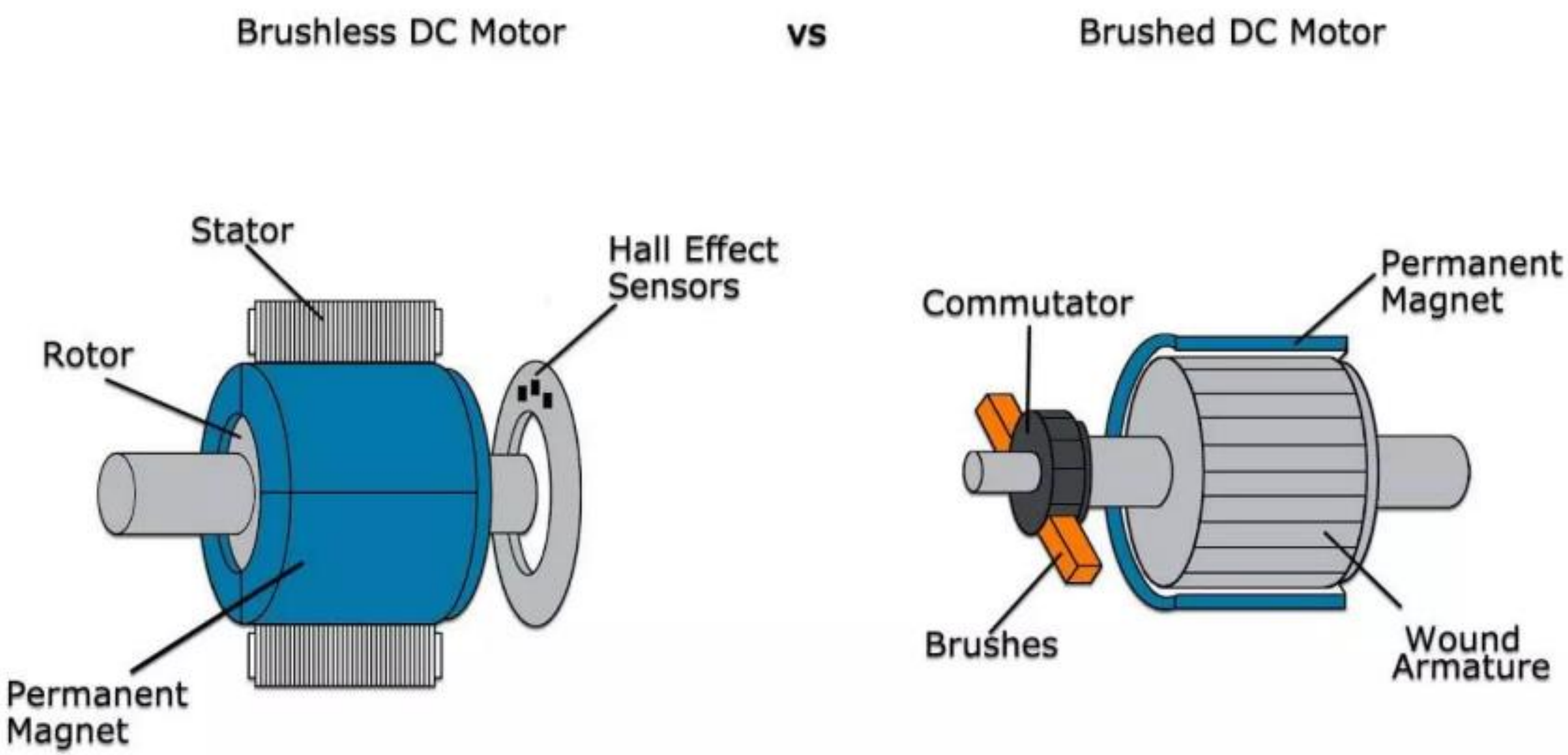
Principle

Brushless permanent magnet d.c. motors

- The rotor is a permanent magnet.
- The coils do not rotate, are fixed in place on the stator.
- As the coils do not move, brushes and commutator are not required.
- Current to the fixed coils is controlled from the outside.
- Rotation is achieved by changing the direction of the magnetic fields generated by the surrounding stationary coils.
- Control of the rotation is by adjusting the magnitude and direction of the current into these coils.






Brushless DC Motor
vs
Brushed DC Motor
Stator
Hall Effect
Sensors
Rotor
Permanent
Magnet
Commutator
Permanent
Magnet
Brushes
Wound
Armature

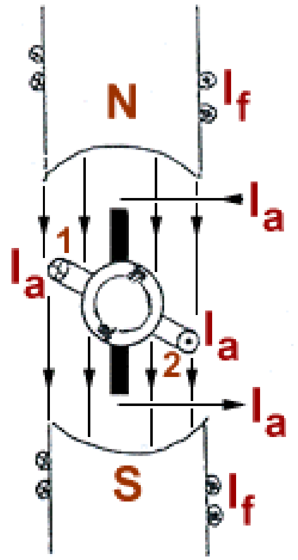
Brushed vs Brushless DC Motors Comparison

Feature	Brushless DC Motor	Brushed DC Motor
Commutation	Electronic commutation based on Hall position sensors	Brushed commutation
Maintenance	Less or no maintenance	Periodic maintenance
Life	Longer	Shorter
Speed / Torque	Enable operations on all speeds with rated load	At higher speeds, brush friction increases and reduce torque
Efficiency	High	Moderate
Speed Range	Higher – No mechanical limitation due to contact	Lower – Mechanical limitations due to brushes
Electric Noise Generation	Low – because it has permanent magnets on the rotor, improves dynamic response	Arcs in the brushes will generate electric noise

Induced EMF in the Armature

- As the coil rotates an emf is induced in each conductor which opposes the externally supplied armature current, I_a.
- The external supply must overcome this emf if the machine is to continue motoring and deliver mechanical power through its shaft.
- Faraday's Law states that the

emf induced in a conductor = rate of change of flux linkages



- Taken over a period of time

$$\textbf{Average emf induced in conductor} = \frac{\textbf{total flux linkage}}{\textbf{total time of linkage}}$$

So, When conductor 1 is close to N-pole:

Total flux emanating from that pole $= \phi$

$$\text{Average } \textit{emf induced in conductor}_1 = \frac{\textit{total flux linkage}}{\textit{total time of linkage}} = \frac{\varphi}{\left(\frac{1}{2n}\right)} = 2n\varphi \text{ Volts}$$

Therefore, if the coil rotating at n rev sec^{-1}

Each conductor will be close to a particular pole 2n times per rotation

Each conductor will link with its magnetic flux for $\left(\frac{1}{2n}\right)$ sec per rotation

- Number of poles affects the induced emf
- Machines have several pairs of poles.
- For a machine with ***p*** pole pairs, the average emf in each conductor is given by:
- average emf induced in a conductor $\Bigg\}$ = $\dfrac{\text{total flux per pole}}{\text{total time conductor is under a pole}}$ $= \dfrac{\varphi}{\left(\dfrac{1}{p} \times \dfrac{1}{2n}\right)} = 2pn\varphi$ **Volts**

Total emf induced in armature winding $\Big\}$ = average emf induced in one conductor × number of armatur conductors in series

$$\mathbf{E} \quad = \quad \mathbf{2pn\phi \times} \quad \mathbf{A_s}$$

The number of poles (2*p*) and the number of armature conductors in series (A_s) are constant for a particular machine. Therefore $k = 2p\,A_s$

$$\boldsymbol{E = k\phi n} \textbf{ Volts}$$

Since the angular velocity, $\omega = 2\pi n$ ➡ $\mathbf{E} = \dfrac{\mathbf{k}}{\mathbf{2\pi}}\varphi\omega$ **Volts**

TORQUE

Electrical power delivered to the armature = Armature emf × Armature current

$$P_a = E \times I_a$$

This power creates the torque to make the armature rotate.

Electrical torque developed in the armature = $\dfrac{\text{Electrical power delivered to the armature}}{\text{Angular velocity}}$

Remember: Power is the rate at which work is done; Work done in 1 s = force × distance

Power = work done / time taken

$$T_e = \frac{P_a}{\omega} = \left(\frac{k}{2\pi}\varphi\,\omega\cdot I_a\right)\frac{1}{\omega} = \frac{k}{2\pi}\varphi\, I_a \quad \textbf{Newton meters}$$

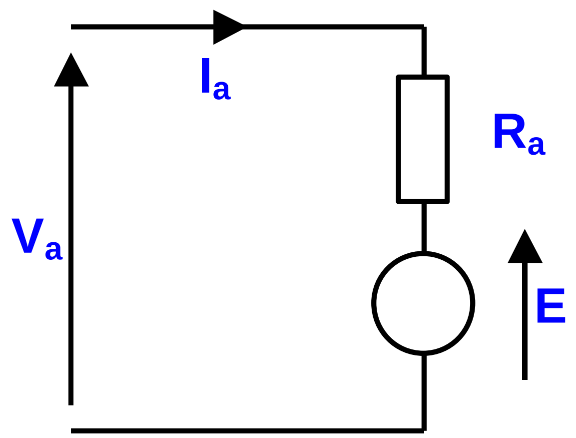
Mechanical torque$|_{\text{at the shaft}}$ = Electrical torque - "Lost" torque$|_{\text{due to frictional and other losses}}$

The "lost" torque is small and will be ignored

Armature Terminal Voltage

- The figure represents an equivalent circuit of an armature
- **E** is the **induced emf**
- R_a is the **armature resistance**
- The armature terminal voltage is given by:

$$V_a = E + I_a R_a$$



Methods of Connection

The field and armature windings may be connected to:

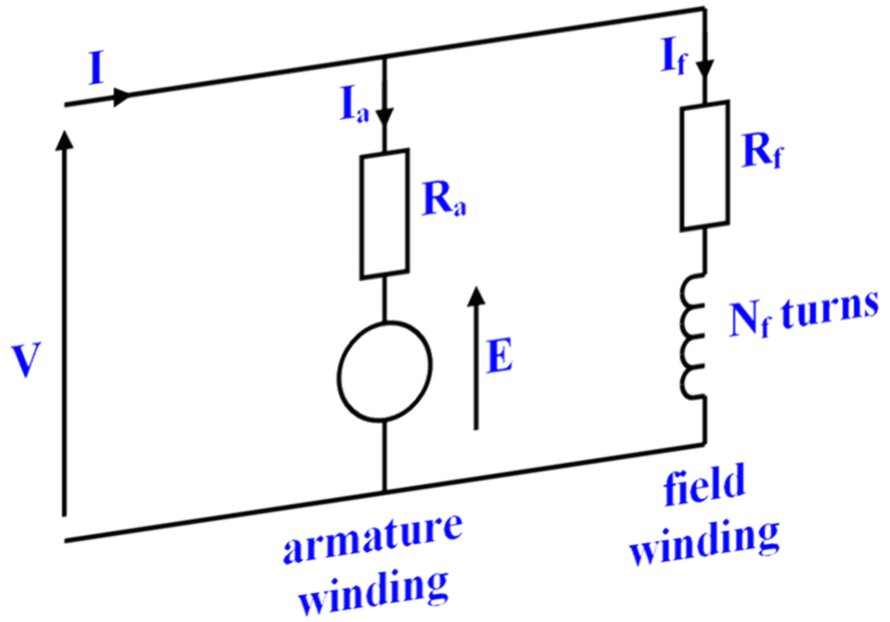
- ❖**Independent supplies - separately excited**
- ❖**Common supply - self excited**
  - ➢ **Shunt wound:** The field and armature windings are connected in parallel
  - ➢ **Series wound:** The field and armature windings are in series
  - ➢ **Compound wound:** Has two field windings;
    - One connected parallel with the armature and
    - Other in series with the armature

Shunt Wound DC Motors

Field Winding:

$$\varphi = \frac{iN}{S} = \frac{I_f N_f}{S}$$

Where, S is the reluctance,
N is the number of turns in the coil and
i is the coil current.



Armature Winding:

Armature terminal voltage, $V = E + I_a R_a$

$$V = k\phi n + I_a R_a$$

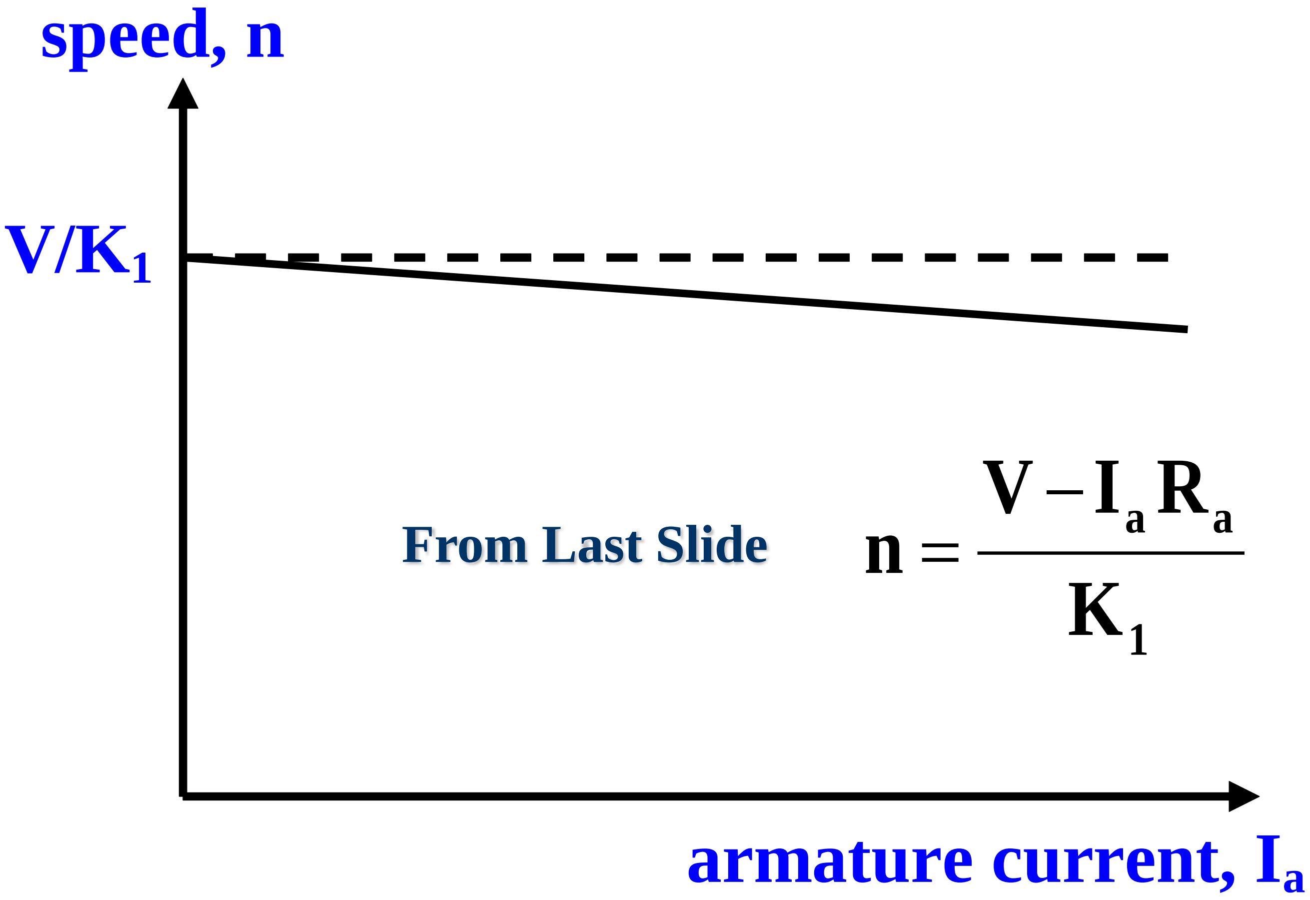
with ϕ constant, let $K_1 = k\phi$ $\quad V = K_1 n + I_a R_a$

V : External supply voltage
R_f : field winding resistance

are normally constant, hence keeping I_f and hence ϕ constant.

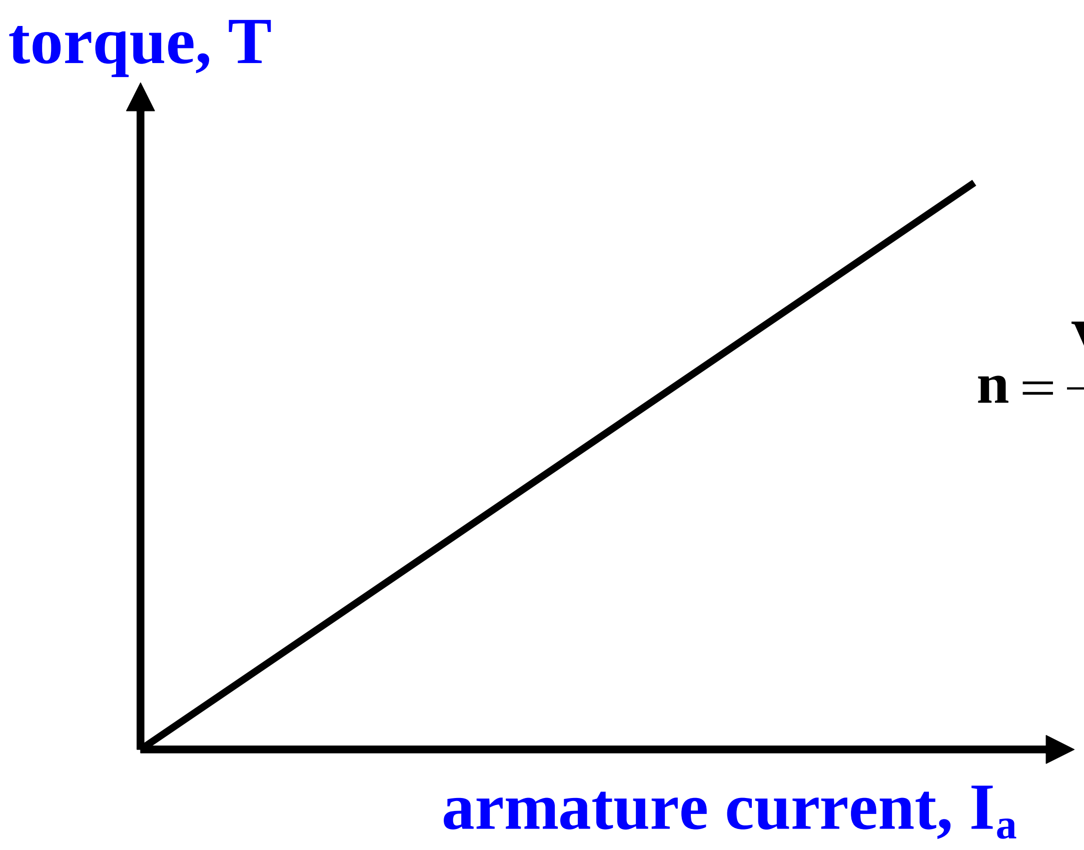
$$\therefore \text{ The steady state speed } = n = \frac{V - I_a R_a}{K_1}$$

Speed Current Characteristics



$$n = \frac{V - I_a R_a}{K_1}$$

Torque Current Characteristics



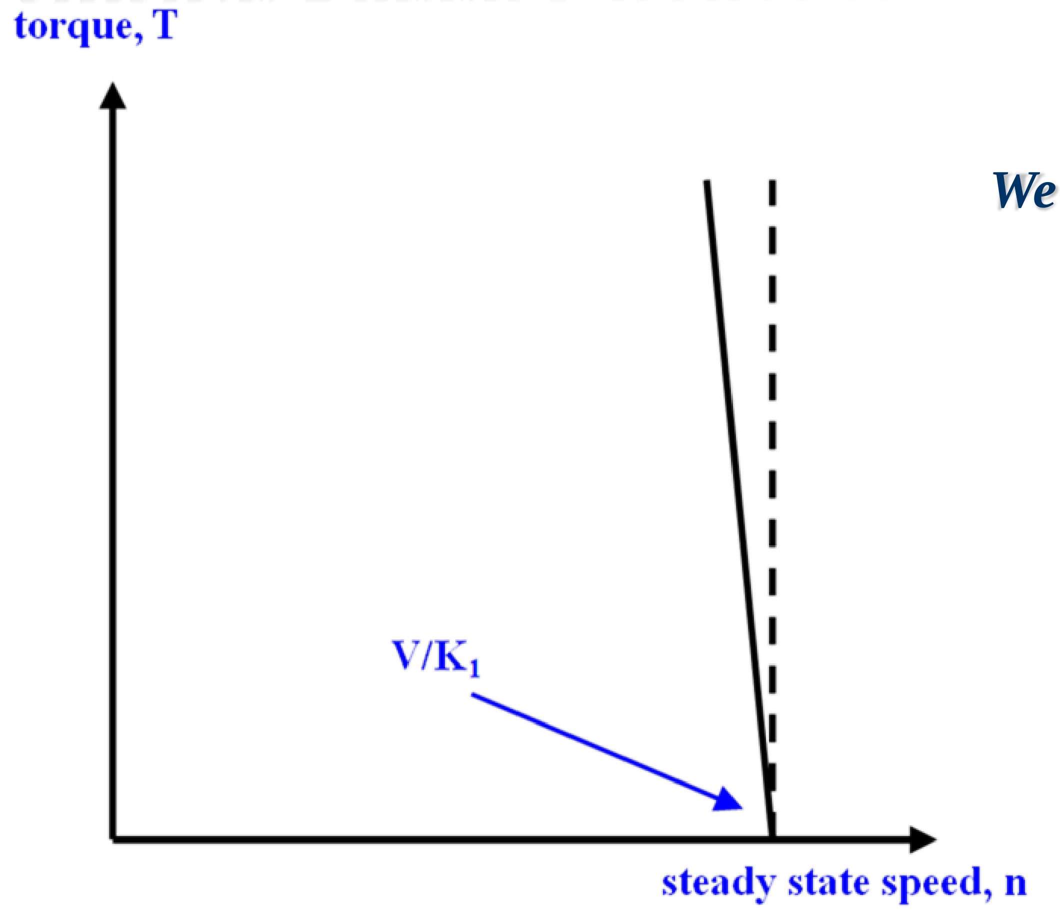
$$n = \frac{V - I_a R_a}{K_1} \quad \text{(from last slide)}$$

Using $T_e = \frac{k}{2\pi}\varphi\, I_a$

With φ constant, $K_2 = \frac{k\varphi}{2\pi}$

$$\therefore \; T = K_2 \cdot I_a \qquad \text{or} \qquad T = \frac{k}{2\pi}\varphi \cdot I_a$$

TORQUE SPEED CHARACTERISTICS



We had:

$$n = \frac{V - I_a R_a}{K_1}$$

$$\Downarrow$$

$$I_a = \frac{V - K_1 n}{R_a}$$

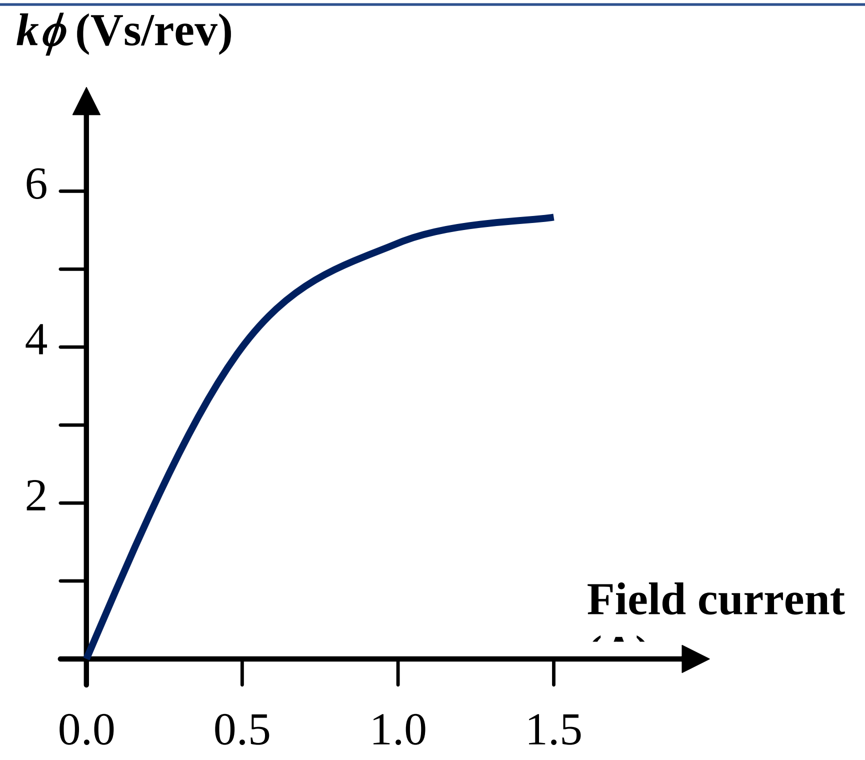
$$\Downarrow$$

$$T = \frac{K_2}{R_a}[V - K_1 n]$$

The torque-speed curve shows that shunt motors can be used to drive fairly constant speed from no load to full torque

Therefore, ideal for use with machine tools, pumps, compressors etc.

NUMERICAL



- A 220V dc shunt motor has an armature resistance of 0.8Ω and field winding resistance of 220Ω. The motor field characteristic [$k\phi$ *versus* field current] is shown in Figure

  a) Calculate the field current

If the motor drives a constant load torque of 17.5Nm, calculate

b) armature current

c) speed

SOLUTION

Field Circuit:

$$I_f = \frac{V}{R_f} = \frac{220V}{220\Omega} = 1\text{ A}$$

from graph $k\phi = 5.5$ Vs[rev]$^{-1}$

Torque equation: $$T = \frac{k\phi}{2\pi} I_a$$

$$17.5 = \frac{5.5}{2\pi} I_a$$

Armature current, $I_a = 20$A

Armature Circuit:

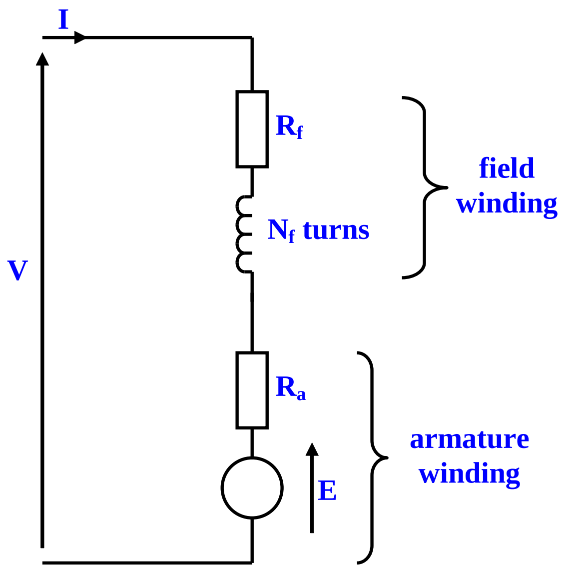
$$V = E + I_a R_a = k\phi n + I_a R_a$$

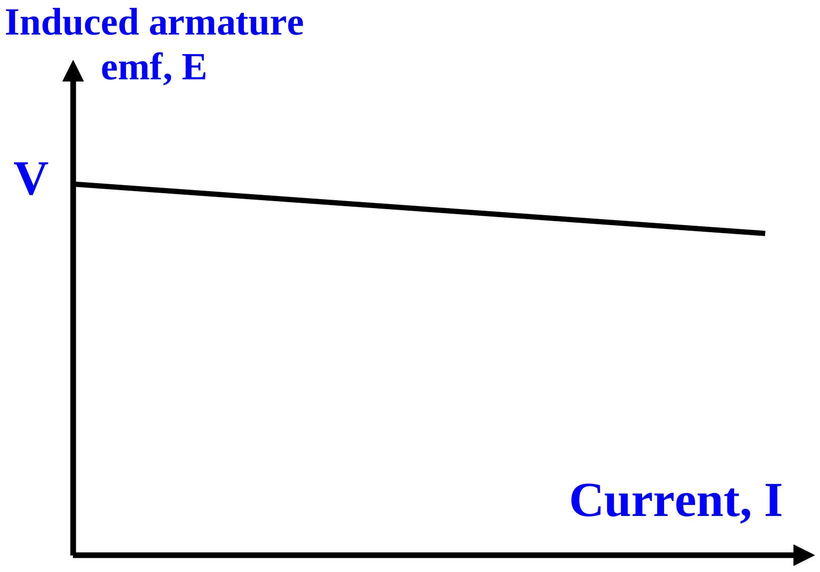
$$220 = 5.5n + 20 \times 0.8$$

$$\therefore \mathbf{n} = \frac{220 - 16}{5.5}$$

Speed = 37.1 rev sec^{-1}
= 2225 rev min^{-1}.

Series Wound DC Motors





In the series motor current, ***I*** flows through both field and armature windings so:

$$V = E + I(R_a + R_f)$$

let $R = R_a + R_f$ ⇨ $V = E + IR$

⇨ $E = V - IR$

NUMERICAL

A 220V dc series motor has armature and field resistances of 0.2Ω and 0.5Ω respectively. When running at 1000 rev min^{-1} the motor draws 10A from the supply. Calculate the torque delivered.

SOLUTION

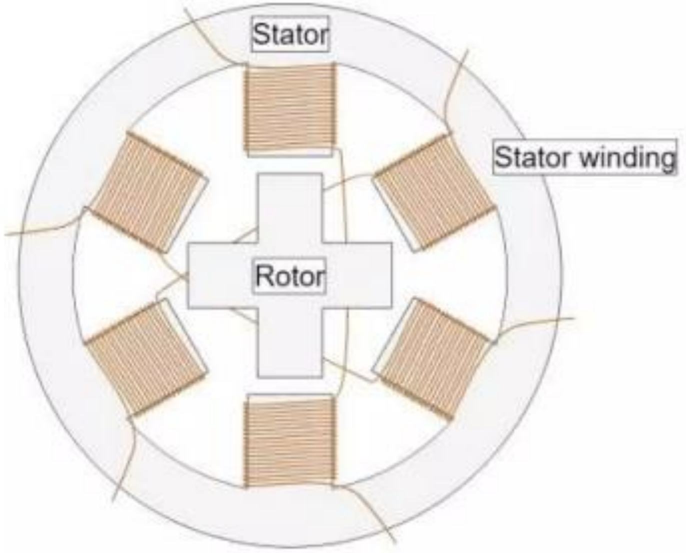
$$V = E + I_a(R_a + R_f)$$
$$220 = E + 10\,(0.2 + 0.5)$$
$$220 = E + 7$$
$$E = 213 \text{ volts}$$

$$T\omega = T(2\pi n) = EI_a$$
$$T = \frac{213 \times 10}{2\pi \times (1000/60)}$$

$$T = 20.34 \text{ Nm}$$

Stepper motor

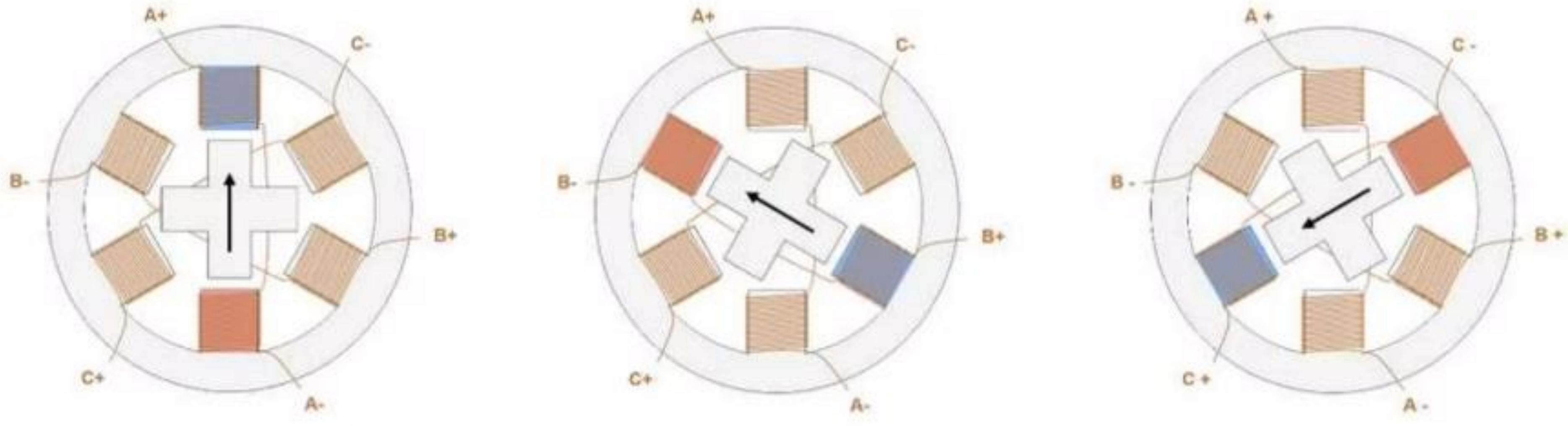
Working Principle of stepper motor



- Stepper Motor is a brushless electromechanical device which converts the train of electric pulses applied at their excitation windings into precisely defined step-by-step mechanical shaft rotation.
- The shaft of the motor rotates through a fixed angle for each discrete pulse.
- This rotation can be linear or angular. It gets one step movement for a single pulse input.

Stepper motor

Working Principle of stepper motor



- At the beginning, coil A is energized and the rotor is aligned with the magnetic field it produces.
- When coil B is energized, the rotor rotates clockwise by 60° to align with the new magnetic field.
- The same happens when coil C is energized.

Classification / Types of Stepper motor

1. Variable reluctance stepper motor.
2. Permanent magnet stepper motor.
3. Hybrid stepper motor.

Stepper Motors Advantages and Disadvantages

Advantages

- Due to their internal structure, stepper motors do not require a sensor to detect the motor position. Since the motor moves by "steps," by simply counting these steps, you can obtain the motor position at a given time.
- Stepper motor control is pretty simple.
- Stepper motors offer good torque at low speeds, are great for holding position, and also tend to have a long lifespan.

Stepper Motors Advantages and Disadvantages

Disadvantages

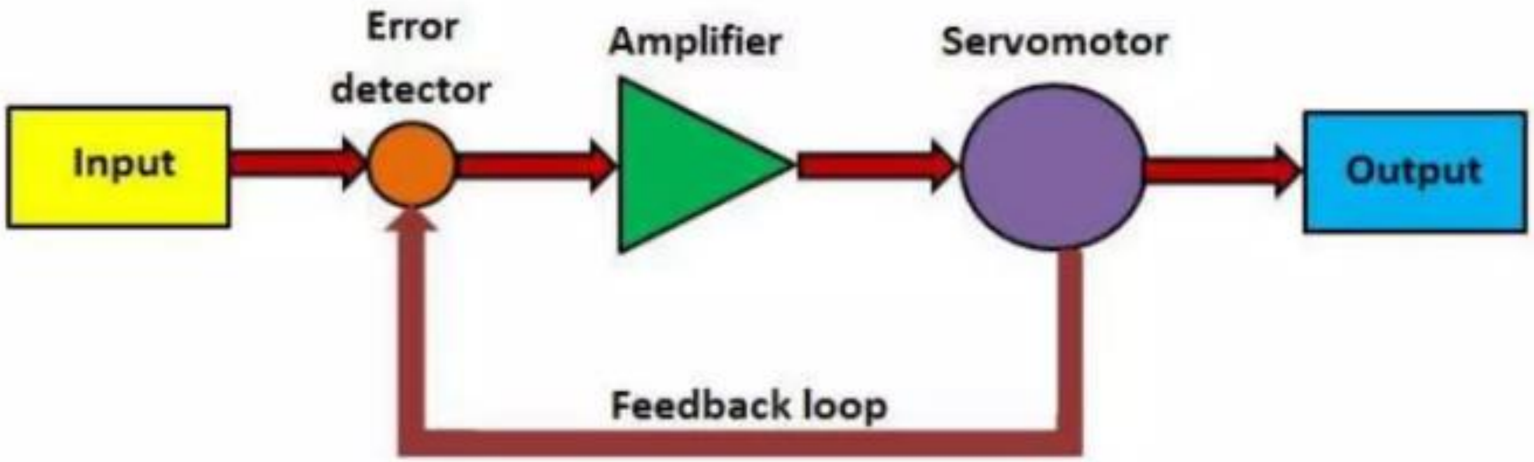
- They can miss a step if the load torque is too high.
- These motors always drain maximum current even when still, which makes efficiency worse and can cause overheating.
- Stepper motors have low torque and become noisy at high speeds
- Stepper motors have low power density and a low torque-to-inertia ratio

Stepper Motors - Applications

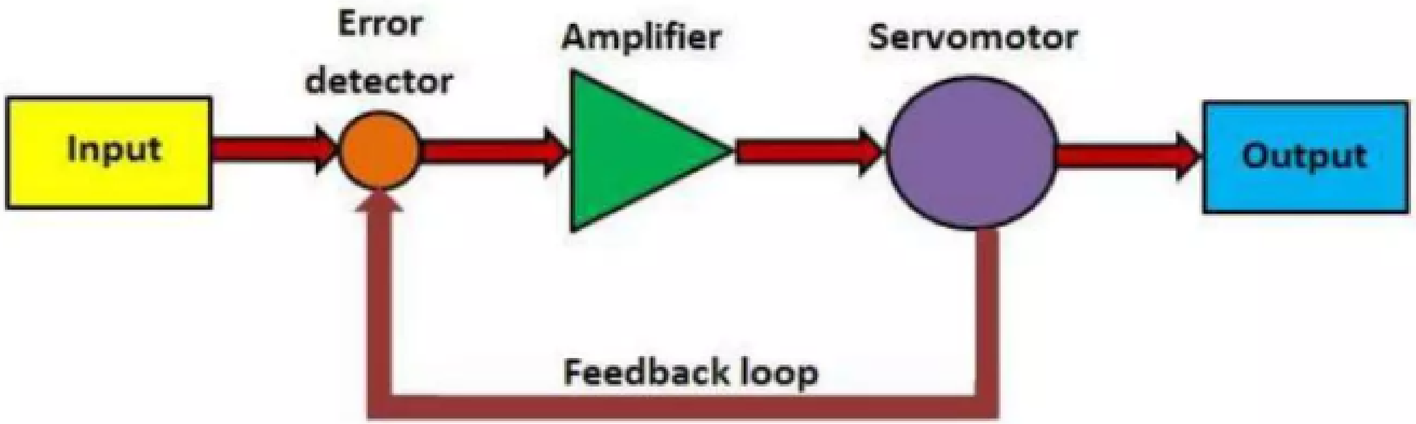
- Factory automation
- Packaging
- Material handling
- Aerospace industry
- Laser measurements
- Robotics

Servo Motor

- Servomotors are special electromechanical devices that produce precise degrees of rotation.
- A servo motor is a DC or AC or brushless DC motor combined with a position sensing device.
- Servomotors are also called control motors as they are involved in controlling a mechanical system.
- The servomotors are used in a closed-loop servo system as shown in Fig.



Servo Motor



- A reference input is sent to the servo amplifier, which controls the speed of the servomotor.
- A feedback device is mounted on the machine, which is either an encoder or resolver. This device changes mechanical motion into electrical signals and is used as a feedback.
- This feedback is sent to the error detector, which compares the actual operation with that of the reference input.
- If there is an error, that error is fed directly to the amplifier, which will be used to make necessary corrections in control action.
- In many servo systems, both velocity and position are monitored.
- Servomotors provide accurate speed, torque, and have ability of direction control.

Advantages of servo motors

- Provides high intermittent torque, high torque to inertia ratio, and high speeds.
- Work well for velocity control.
- Available in all sizes.
- Quiet in operation.
- Smoother rotation at lower speeds.

Disadvantages of servo motors

- More expensive than stepper motors.
- Require tuning of control loop parameters.
- Not suitable for hazardous environments or in vacuum
- Excessive current can result in partial demagnetization of DC type servo motor

Numerical on Stepper Motor

In a Robotic system, a controlled variable speed motor brings a 3.5° step change. Calculate the number of steps to be traversed by the motor to complete 50 revolutions.

Sol :

A stepper motor can give controlled rotational steps by controlling the rate at which the digital pulses are applied

- Step angle (β) is the angle subtended by rotor position when one pulse is applied to the input of the stator It is a measure of rotor position in degrees

So,

β x No. of revolutions = Total revolutions in degrees

β x N = TR

$$N = \frac{TR}{\beta}$$

1 revolution = 360°

50 revolutions = 50 x 360°

$$N = \frac{50\ x\ 360}{3.5}$$ = 5142.85 = **5243** number of steps/revolutions

Principle

A C Motors

- The motor that converts the alternating current into mechanical power by using an electromagnetic induction phenomenon.
- The stator and rotor are the two most important parts of the AC motors.
- The AC motor may be single phase or three phase (polyphase).
- In the case of DC motor, a current is passed through the coil, generating a torque on the coil. Typical components include a stator and a rotor.
- The armature of rotor is a magnet unlike DC motors and the stator is formed by electromagnets similar to DC motors.

Principle

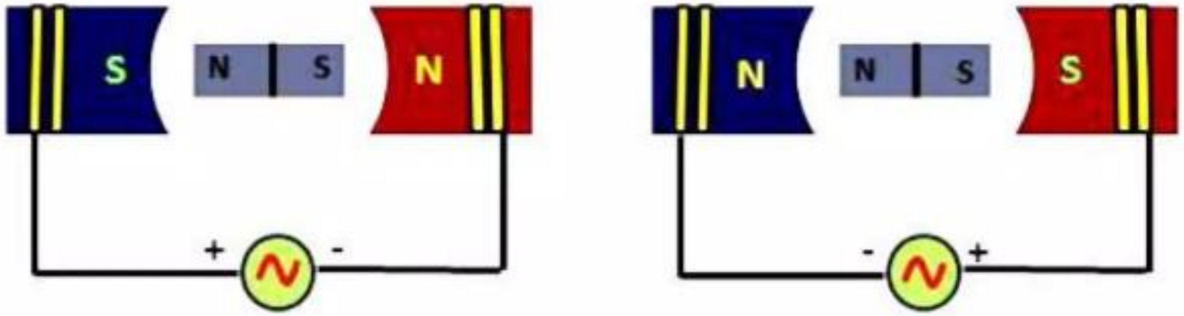
A C Motors - Limitations

- The main limitation of AC motors over DC motors is speed control is more difficult.
- To overcome this limitation, AC motors are equipped with variable frequency drives but the improved speed control comes together with a reduced power quality.

Principle

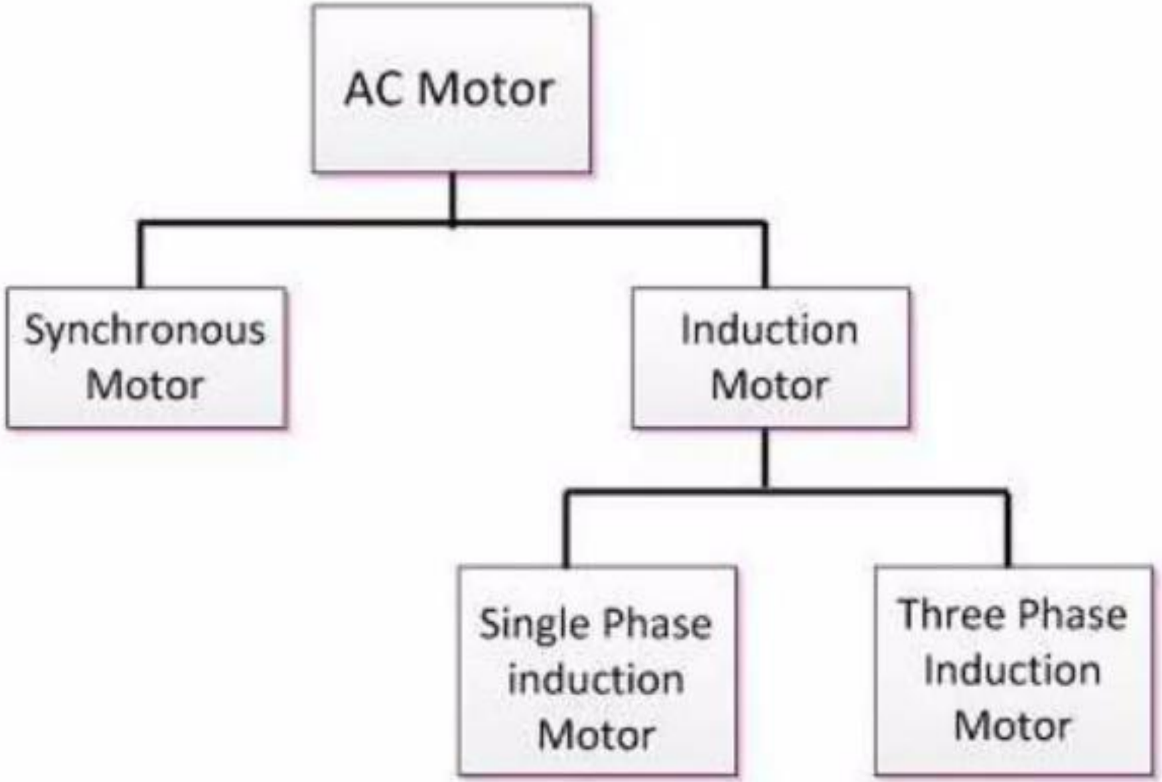
A C Motors

- An AC motor works by applying alternating current to stator windings, which produce a rotating magnetic field.
- The rotor will rotate via the magnetic field and create torque on the drive shaft.
- The speed of rotation varies based on the number of magnetic poles in a stator.
- This speed is called synchronous speed.
- Current flowing through conductors energizes the magnets and develops N and S poles. The strength of electromagnets depends on current. First half cycle current flows in one direction and in the second half cycle it flows in opposite direction. As AC voltage changes the poles alternate.



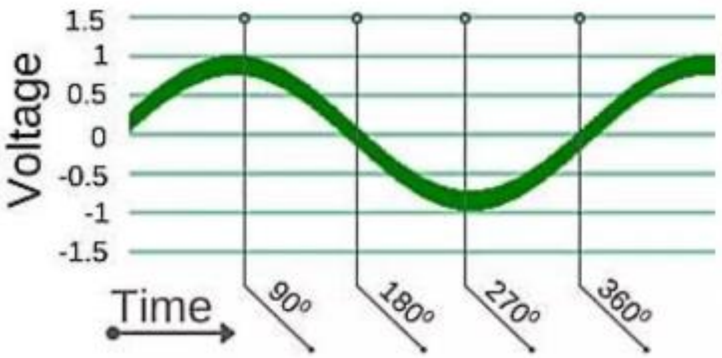
Principle

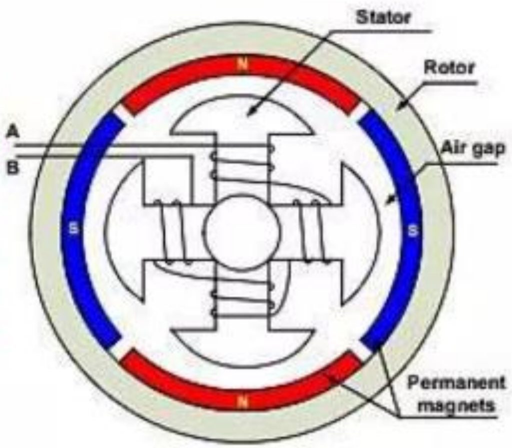
A C Motors classification



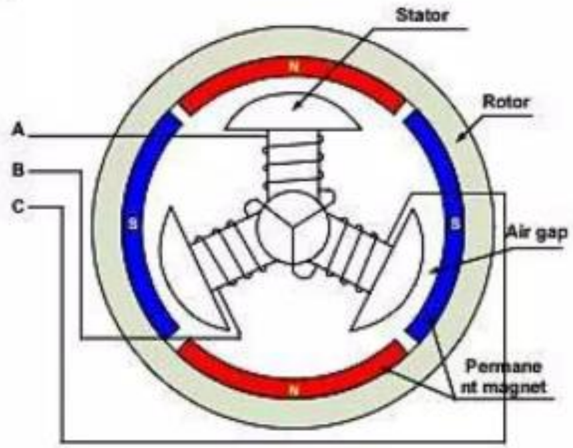
Difference Between Single Phase and Three Phase AC Power Supplies

- A single phase AC has peak voltage at 90º and 270º, in a complete cycle of 360º.
- With the peaks and dips in voltage, power is not delivered at a constant rate.
- In a single phase system, there is one neutral wire and one power wire with current flowing between them.





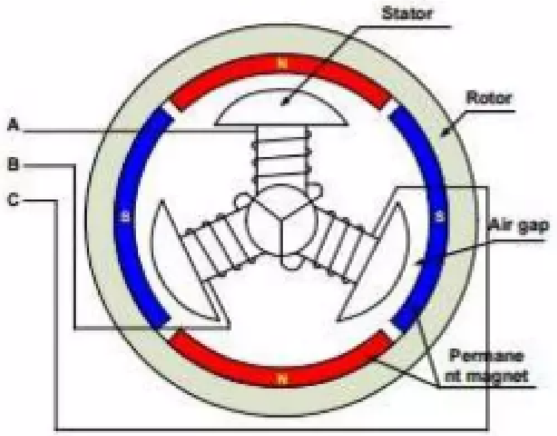
Single-phase



Three-phase

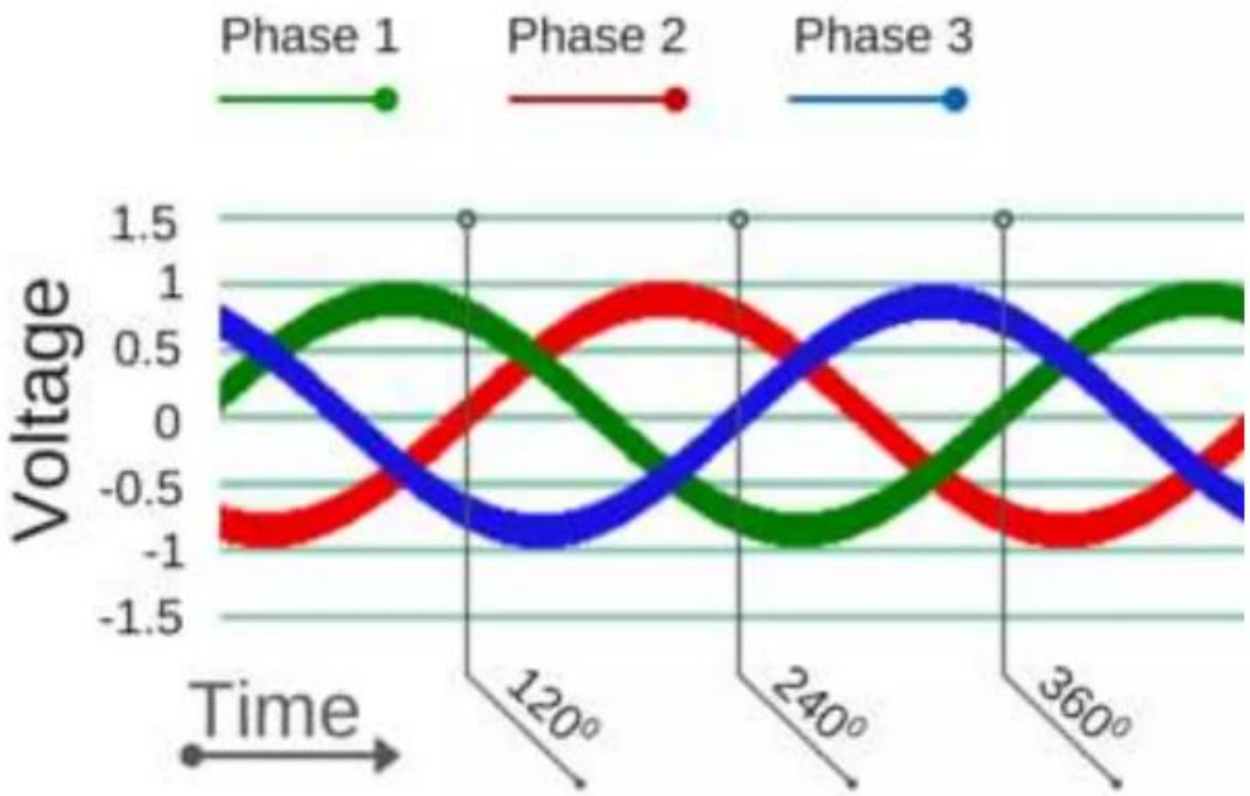
Difference Between Single Phase and Three Phase AC Power Supplies

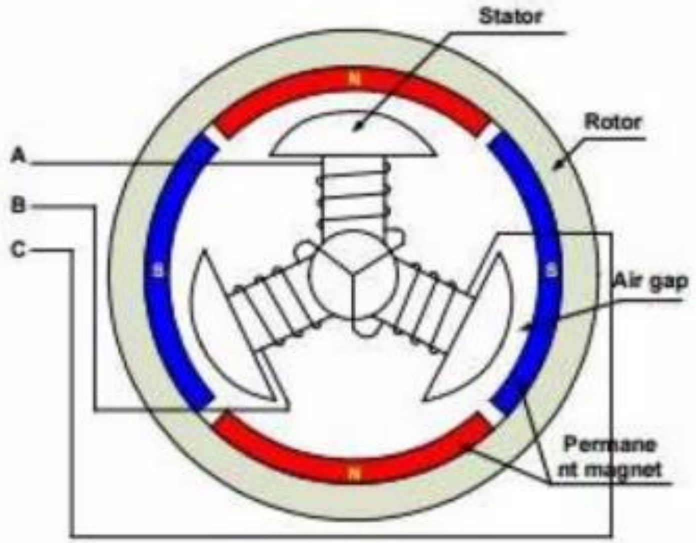
- In a 3 phase system there are three power wires, each 120º out of phase with each other.
- Delta and wye are the two types of circuits use to maintain equal load across three phase system, each resulting in different wire configurations.
- In the delta configuration, no neutral wire is used.
- The wye configuration uses both a neutral and a ground wire.
- In three phases, power enters the cycle by 120º.
- In a cycle of 360º, three phases of power have each peak voltage twice.
- A steady power is delivered at a constant rate, making it possible to carry more load.



Three-phase

Difference Between Single Phase and Three Phase AC Power Supplies

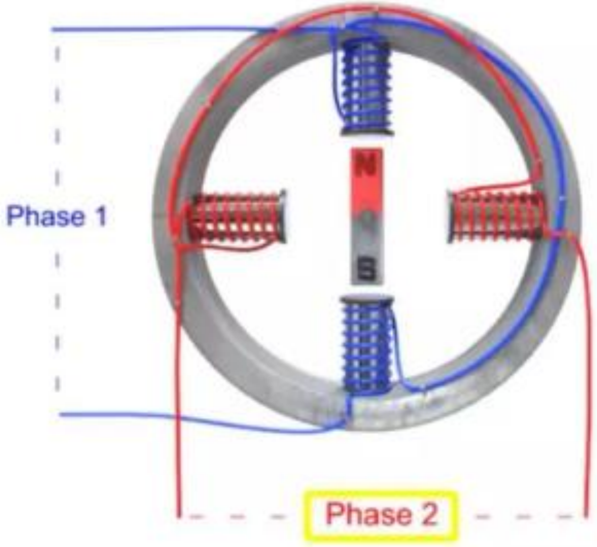




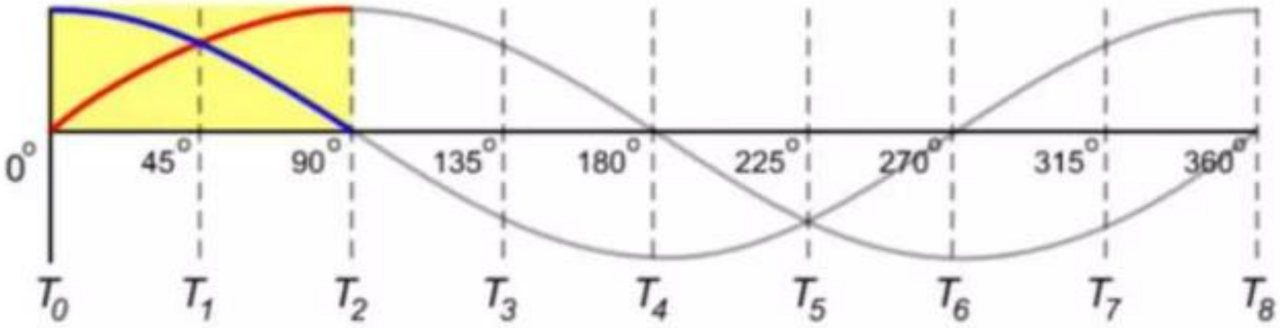
Three-phase

A C Motors

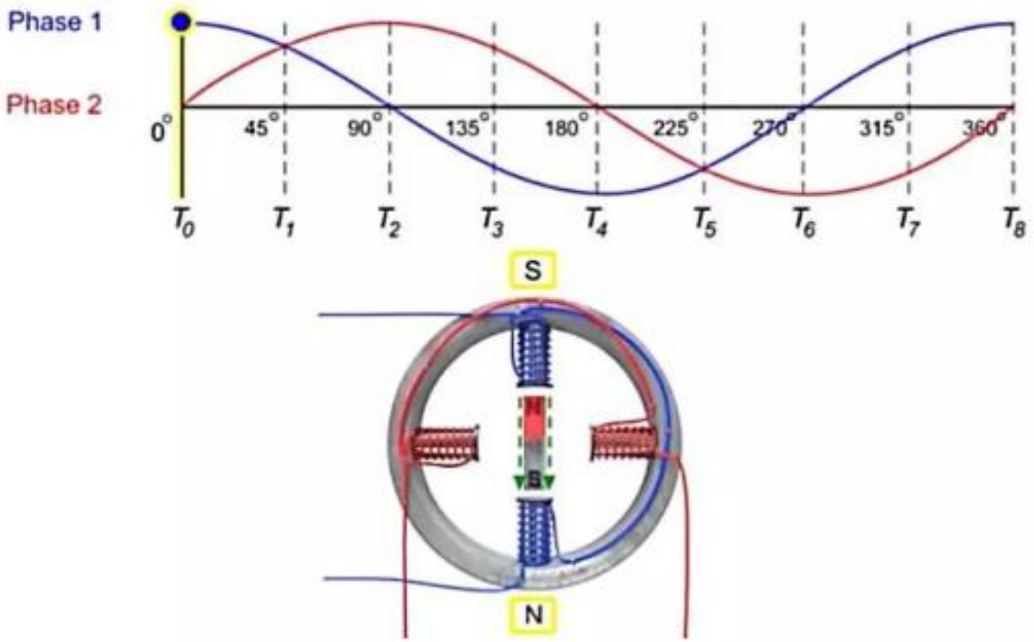
Working Principle of Two Phase Motor

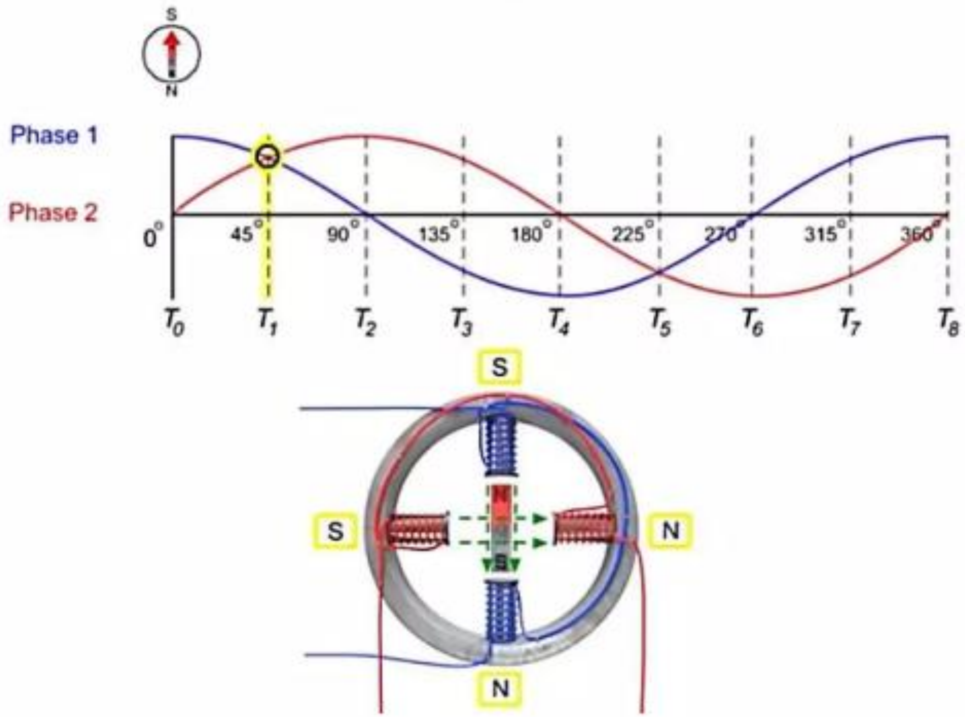


- It consists of a stationary electro magnetic coils (stator).
- Stator positioned under rotating magnet (Rotor).
- Pair of stators are connected to AC input (Phase 1)
- Another pair of stators are connected to AC input (Phase 2)
- The two phases are 90º out of phase
- This phase discrepancy is the key to create the rotation.

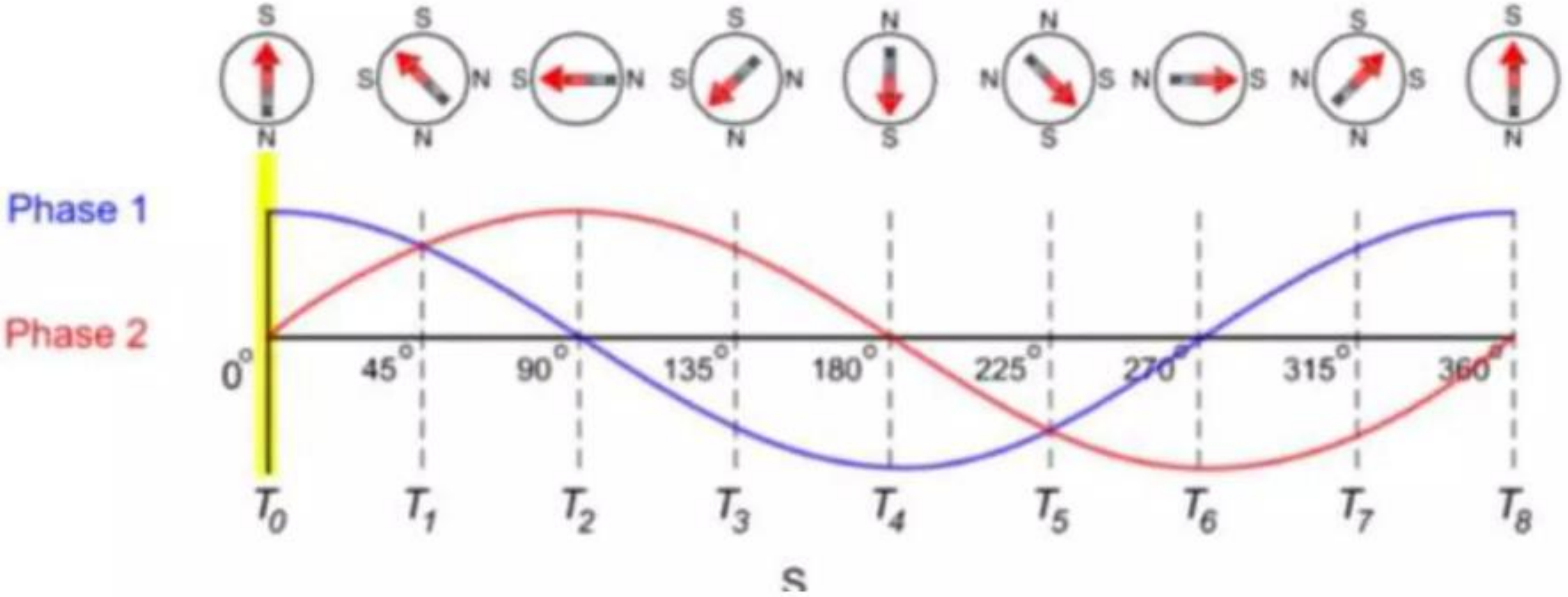


- Amount of current applied to the phase 1 and phase 2 stators at various time intervals along with the respective sine waves (A C).
- The 90° offset between these two sine waves causes the polarity of the stators to change.



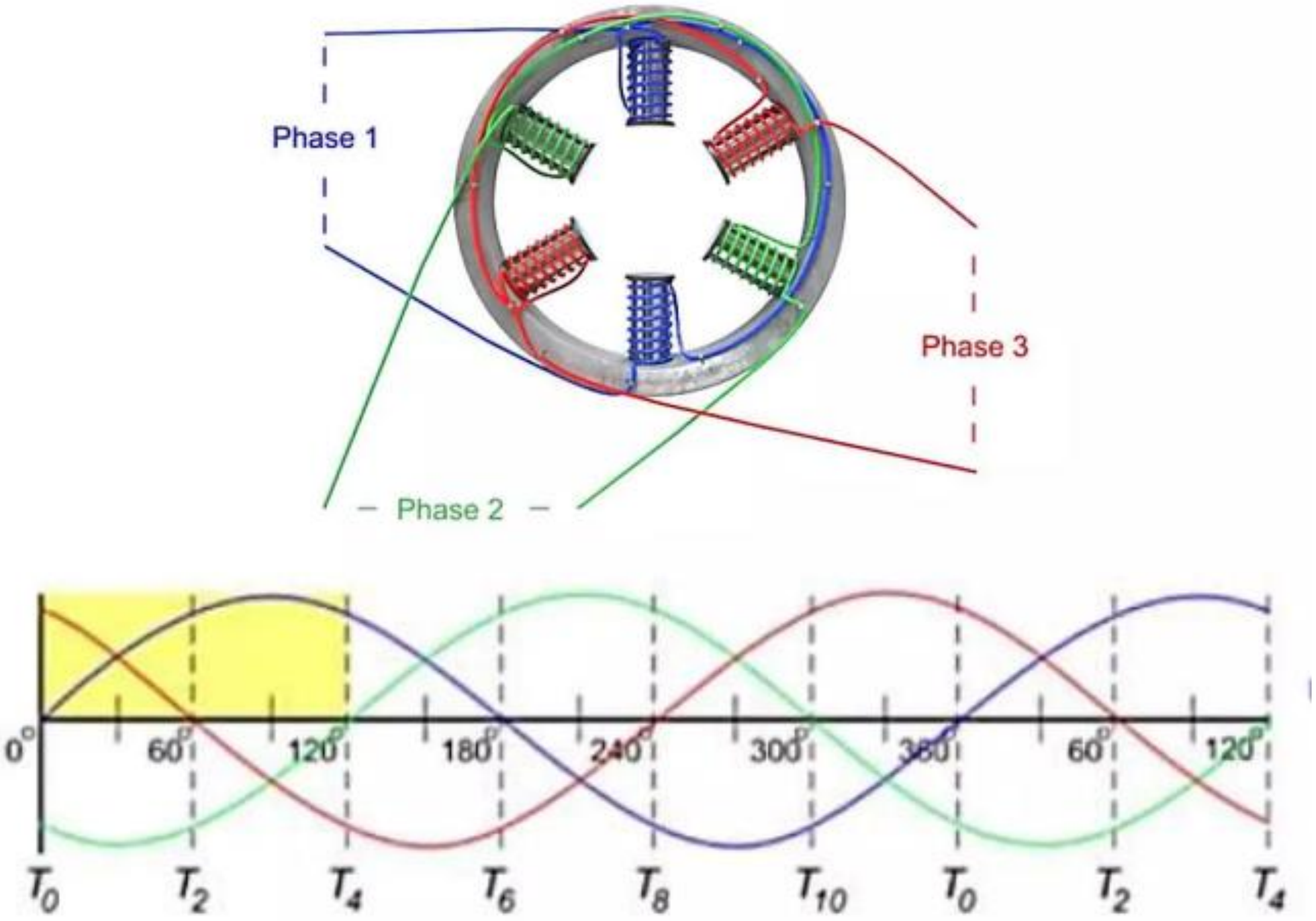


Working Principle of Two Phase Motor

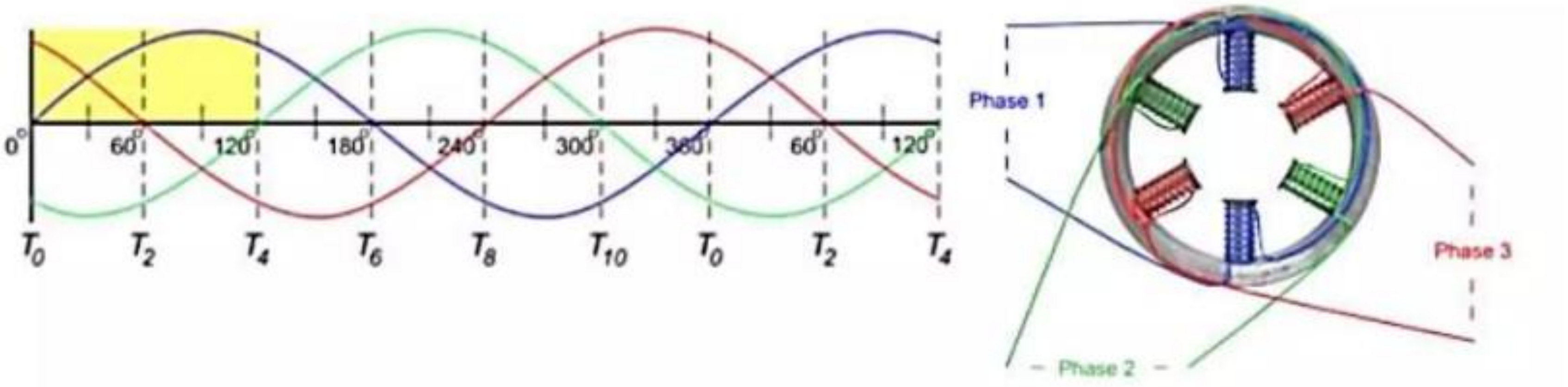


A C Motors

Working Principle of Three Phase Motor



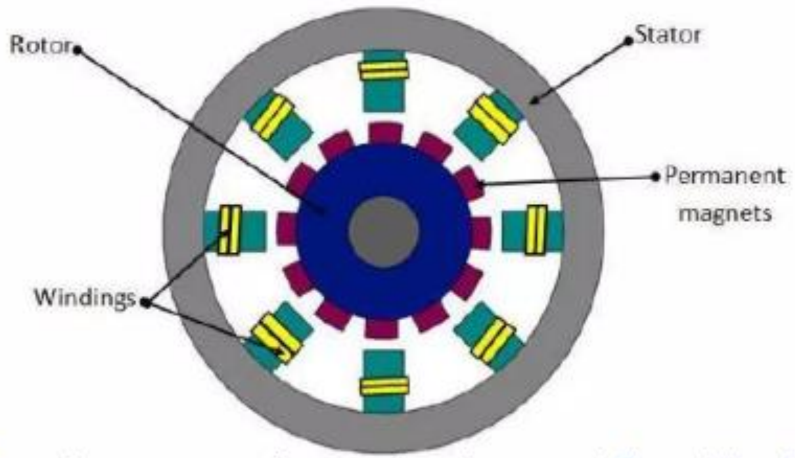
Three Phase Motor



Two Phase Motor

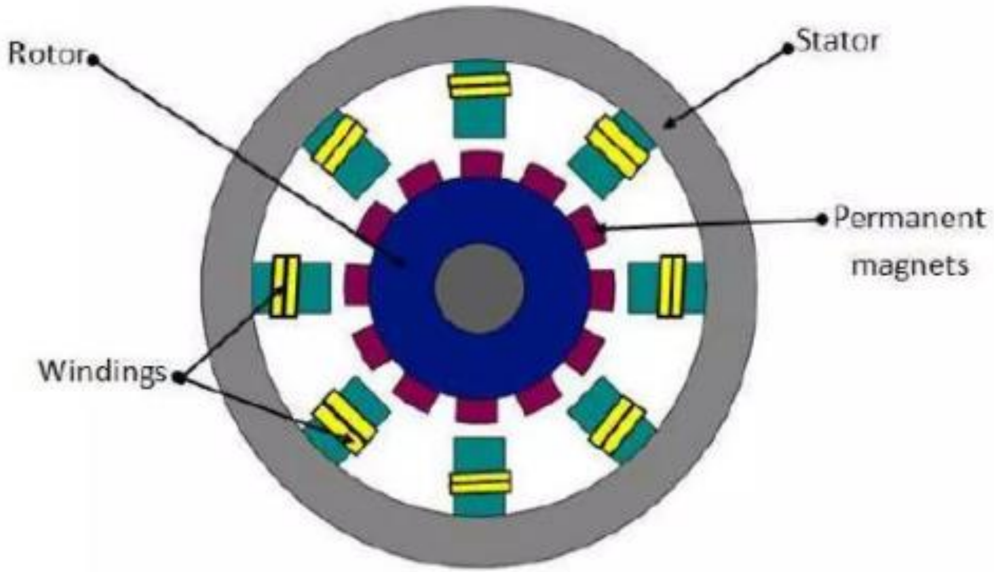
Synchronous motor

Working Principle of Synchronous motor



- A synchronous motor is an AC motor, runs at constant speed fixed by frequency of the system.
- It requires direct current (DC) for excitation and has low starting torque.
- It has two basic electrical parts i.e. stator and rotor as shown in fig.
- The stator consists of individual wounded electro-magnets arranged in such a way that they form a hollow cylinder.
- The stator produces a rotating magnetic field that is proportional to the frequency supplied.
- The rotor consists of a permanent magnets arranged around a cylinder, with the poles facing toward the stator poles.

Working Principle of Synchronous motor



- The main difference between the synchronous motor and the induction motor is that the rotor of the synchronous motor rotates at the same speed as the rotating magnet.
- The stator is given a three phase supply. As the polarity of the stator progressively change the magnetic field rotates, the rotor will rotate with the magnetic field of the stator.
- If a synchronous motor loses lock with the line frequency it will stall. It cannot start by itself, hence has to be started by an auxiliary motor.

Inertial Measurement Unit (IMU)

IMU (Inertial Measurement Unit)

Accelerometer

Acceleration along 3 axes

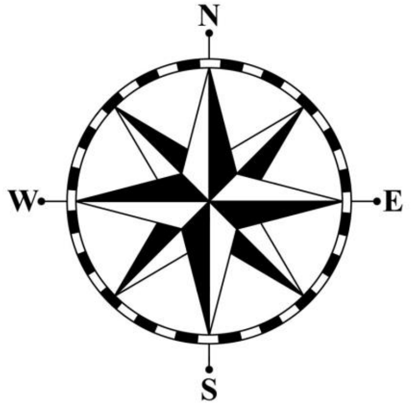
$\{\frac{d^2x}{dt^2}, \frac{d^2y}{dt^2}, \frac{d^2z}{dt^2}\}$

Gyroscope

Rotation speed around 3 axes

$\{\frac{d\theta_x}{dt}, \frac{d\theta_y}{dt}, \frac{d\theta_z}{dt}\}$

Magnetometer (Compass)



Direction of magnetic north

$\{m_x, m_y, m_z\}$

Popular since they are inexpensive, small, and power efficient

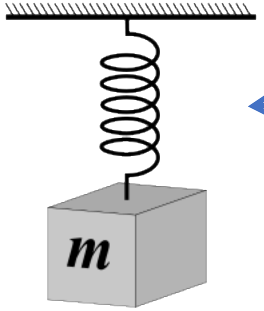
Can be embedded inside any object to enable intelligence

Accelerometer

Basic model (1D)

$\uparrow$

ma_{accl}



Accelerometer measures $\frac{F_k}{m}$

$$F_k = mg$$

$$A_{measured} = \frac{F_k}{m} = g$$

Accelerometer output under rest is non-zero. It measures g

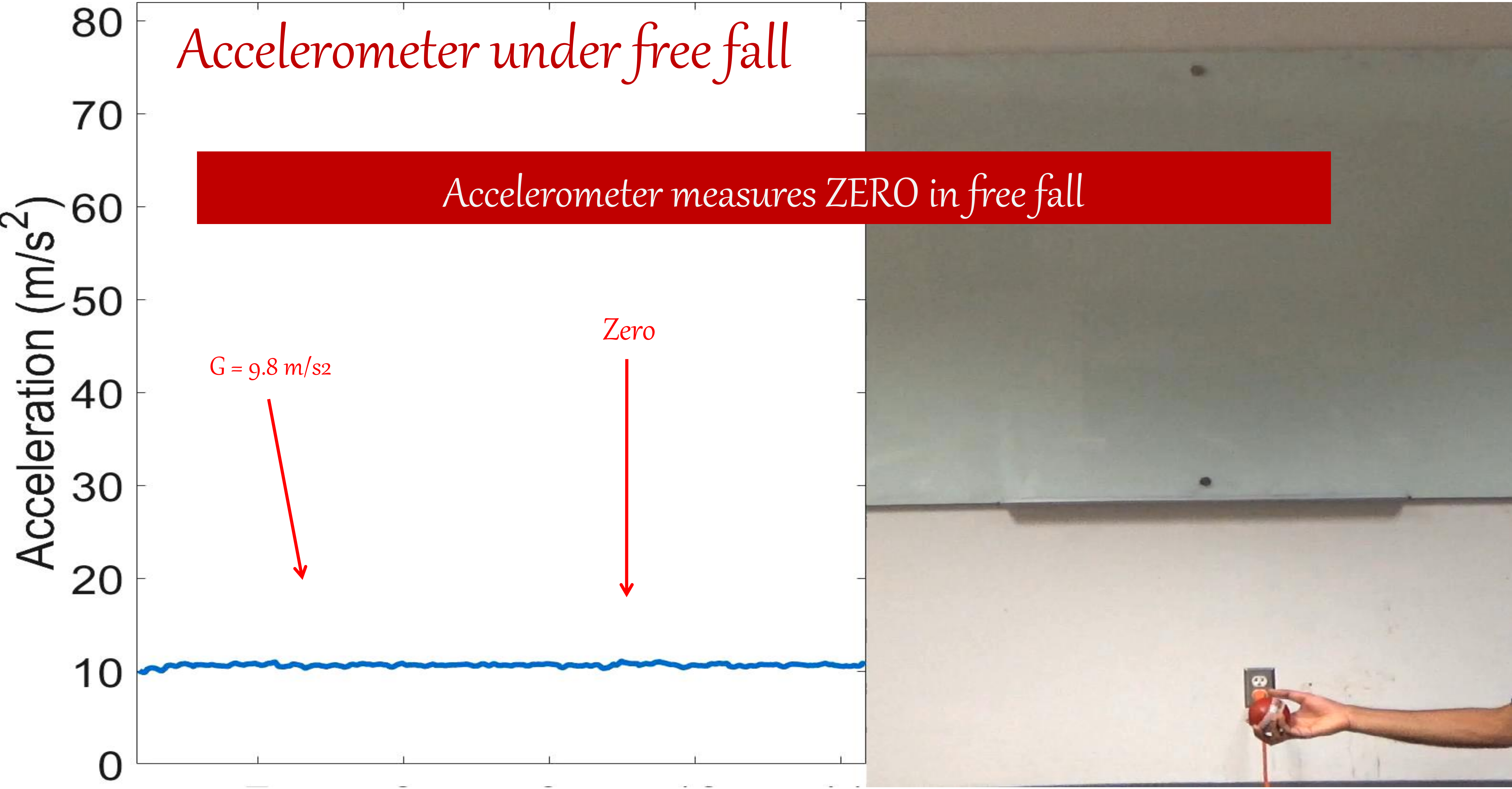
$$ma_{accl} = F_k - mg$$

$$A_{measured} = \frac{F_k}{m} = g + a_{accl}$$

Accelerometer output under motion

Accelerometers measure sum of acceleration due to motion and gravity

Smartphone accelerometers are tri-axial – can measure 3D acceleration


Accelerometer under free fall
Accelerometer measures ZERO in free fall
G = 9.8 m/s2
Zero
Acceleration (m/s^2)
80
70
60
50
40
30
20
10
0

Measuring linear motion (1D)

$$A_{measured} = g + a_{accl}$$

$$a_{accl} = A_{meas} - g$$

Need to subtract gravity to obtain acceleration due to motion

$$\frac{d^2x}{dt^2} = \mathrm{A_{meas}} - \mathrm{g}$$

$$\frac{d^2x}{dt^2} = \mathrm{A_{meas}} - \mathrm{g} + \mathrm{n}$$

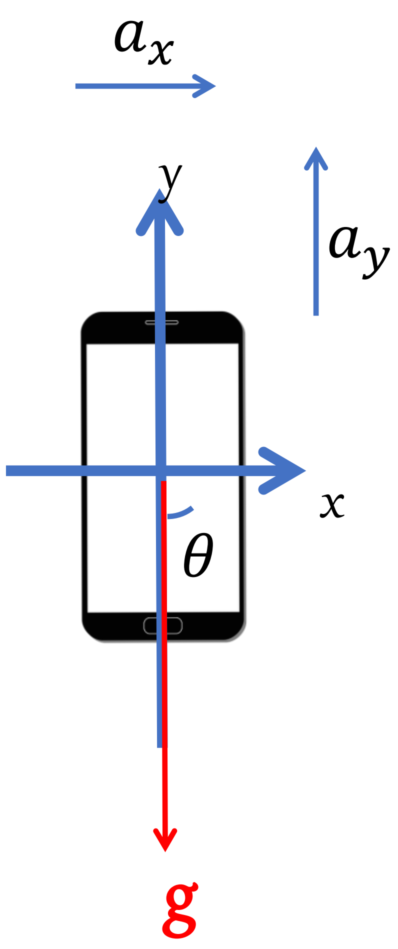
Hardware noise

$$\frac{dx}{dt} = \int (A - g + n)\,dt = \int (A - g)dt + \int n\,dt$$

$$x = \iint_0^t (A - g)dt + \iint_0^t n\,dt$$

Error accumulates dramatically with time

Subtraction of gravity non-trivial in 2D or 3D



Subtraction of gravity in 2D

1D equation → $A_{meas} = a_{accl} + \ g$

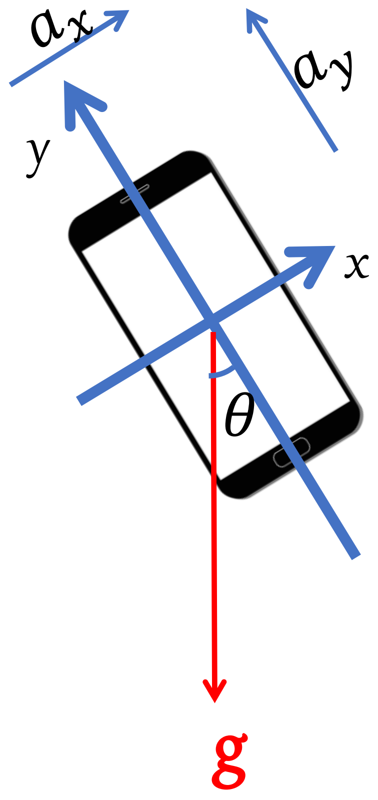
2D equations (y axis pointing upwards)

$$A_x = \ a_x$$

$$A_y = a_y + \ g$$

Subtraction of gravity in 2D

1D equation → $A_{meas} = a_{accl} + g$



2D equations (y axis pointing upwards)

$$A_x = a_x$$
$$A_y = a_y + g$$

2D equations (arbitrary rotation of phone)

$$A_x = a_x + gsin\theta$$
$$A_y = a_y + gcos\theta$$

We need to know the the orientation θ to subtract gravity

Inaccurate orientation will not eliminate gravity, resulting in errors (which accumulate over time)

An interesting idea

2D equations (arbitrary rotation of phone)

$$A_x = a_x + gsin\theta$$

$$A_y = a_y + gcos\theta$$

Suppose the phone is at rest, then $a_x = 0, a_y = 0$

$$A_x = gsin\theta$$

$$sin\theta = \frac{g}{A_x}$$

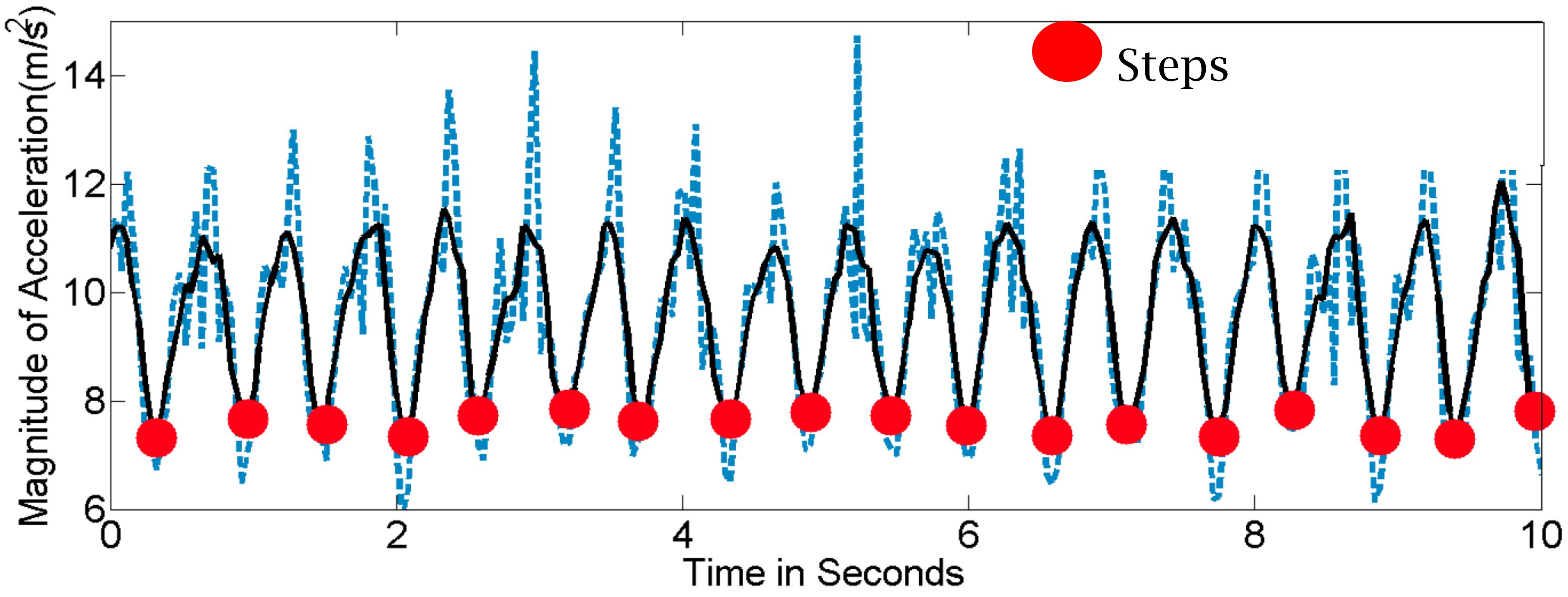
Accelerometer is an orientation sensor!!

Need the accelerometer to be at rest to estimate rotation

However accelerometer alone is not sufficient if we need 3D orientation, more later ..

Accelerometer to measure distance

- Double integration fails dramatically – $x = \iint_0^t (A - g)dt + \iint_0^t n\, dt$
- However, accelerometer is good in tracking steps



Distance = step_count * step_size

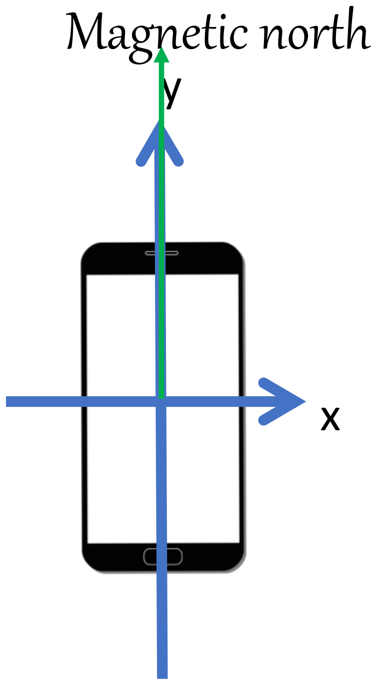
Combining distance estimates with compass directions, we can dead reckon

Accelerometer

- Measures gravity + linear acceleration
- When static, gravity measurement can be used to sense orientation
- Double integrating accelerometer will accumulate error dramatically, step counting is reasonable

Magnetometer

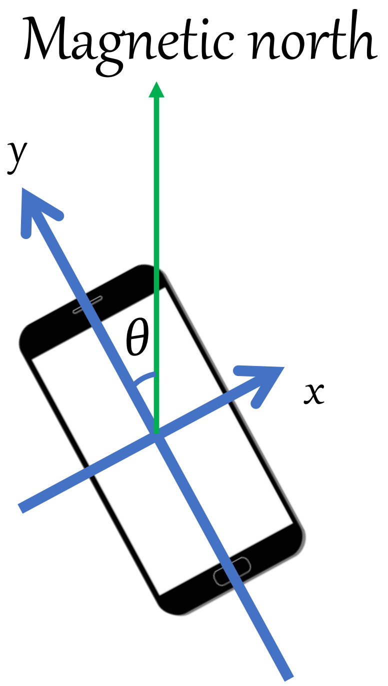
Measures magnetic north (2D example)



Consider a 2D example

$$M_y = M$$
$$M_x = 0$$

Measures magnetic north (2D example)



Suppose, phone rotates in 2D by an angle

$$M_y = M cos\theta$$
$$M_x = M\ sin\theta$$

The same concept generalizes to 3D,
3D magnetometer output $\{M_x, M_y, M_z\}$ depends on phone orientation

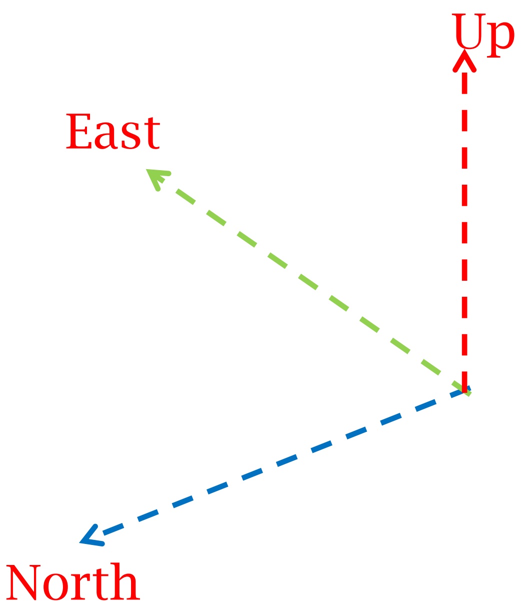
Magnetometer can be used to sense the orientation

$$sin\theta = \frac{M_x}{M}$$

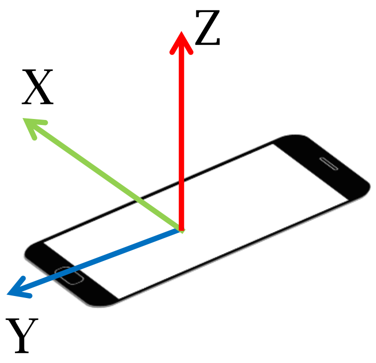
However, in 3D magnetometer alone is insufficient to determine the orientation

3D orientation

Foundations of 3D Orientation

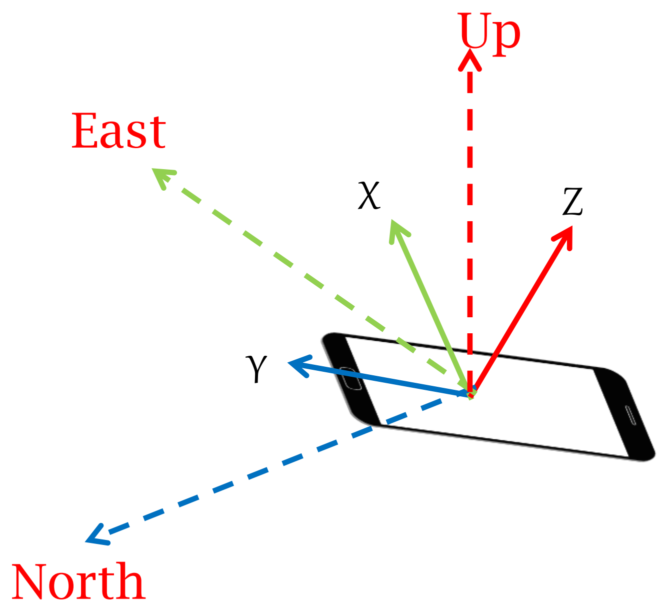


Global Frame



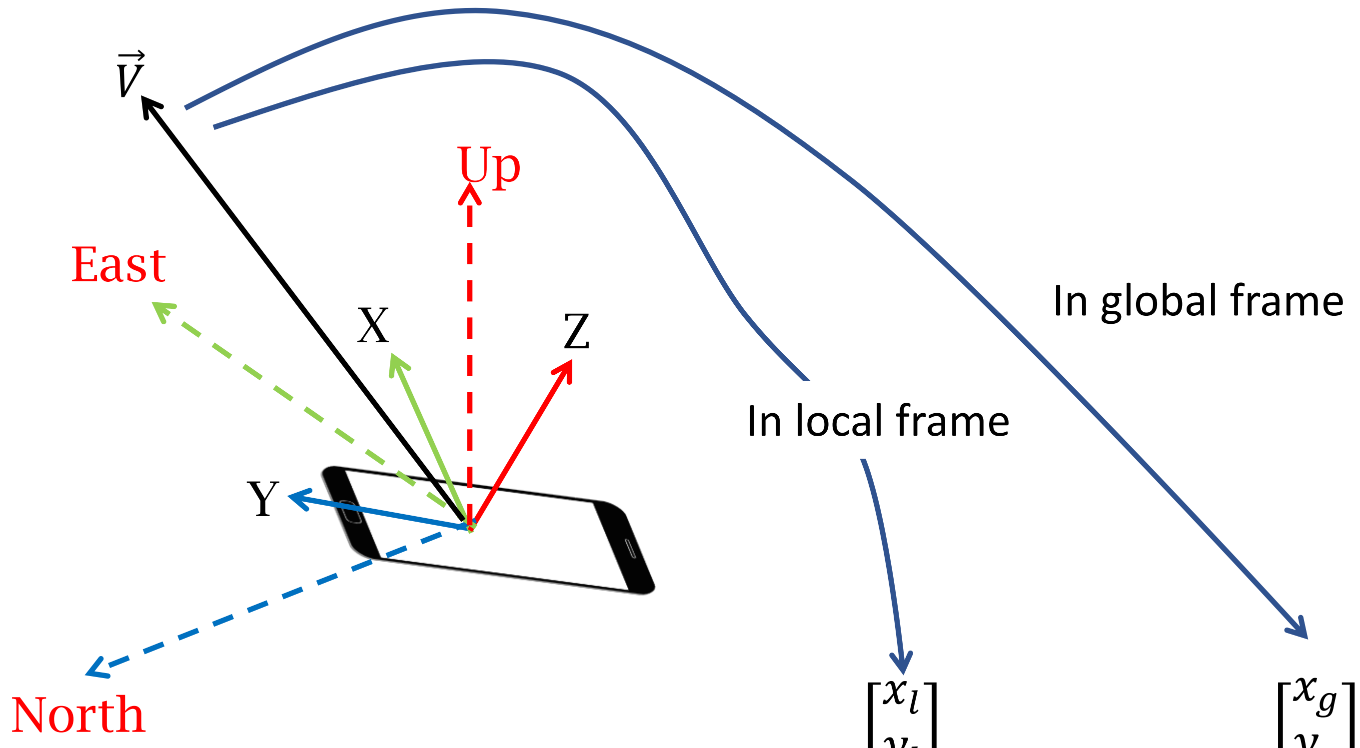
Local Frame

Consider a phone in random orientation



3D Orientation captures the misalignment between global and local frames

Rotation Matrix



$$\begin{bmatrix} x_l \\ y_l \\ z_l \end{bmatrix} \qquad \begin{bmatrix} x_g \\ y_g \\ z_g \end{bmatrix}$$

R is the 3x3 Rotation Matrix

3 x 3 Rotation matrix captures the full 3D orientation

How can we estimate rotation matrix?

Key idea → use globally known reference vectors

which can also be measured in the local frame of reference

- Gravity
- Magnetic North

Gravity equation

Gravity globally known, measurable in local frame with accelerometer

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \boxed{\text{Matrix R}} \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix} \qquad \begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} = \boxed{\text{Matrix R}} \begin{bmatrix} 0 \\ M \\ 0 \end{bmatrix}$$

Magnetic north, globally known, measurable in local frame with magnetometer

6 equations and 9 unknowns (3x3 rotation matrix) can we solve ?

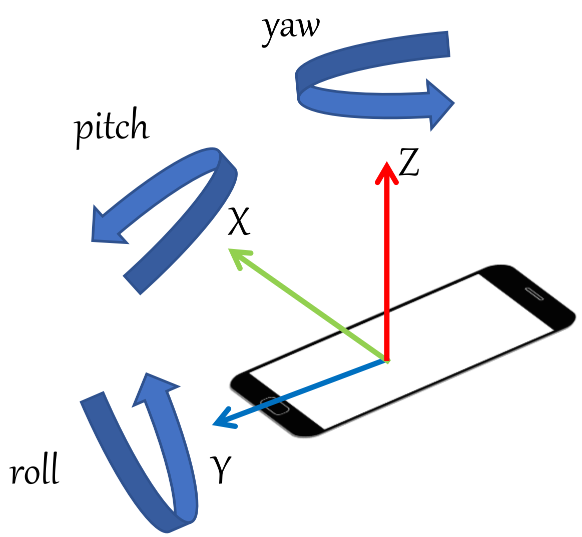
Yes, these 9 unknowns are all not independent (rotation matrix satisfies special properties)

- It does not change length of a vector
- Columns are orthogonal unit vectors

The above 6 equations are sufficient to solve the rotation matrix

Accelerometer and Magnetometer can be used to determine the rotation matrix (3D orientation)

Decomposing the rotation matrix



$$\begin{bmatrix} \text{3x3 Rotation Matrix} \\ R \end{bmatrix} = \begin{bmatrix} \cos(pitch) & 0 & -\sin(pitch) \\ 0 & 1 & 0 \\ \sin(pitch) & 0 & \cos(pitch) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(roll) & \sin(roll) \\ 0 & -\sin(roll) & cos(roll) \end{bmatrix} \begin{bmatrix} \cos(yaw) & -\sin(yaw) & 0 \\ \sin(yaw) & \cos(yaw) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Orientation can be represented as 3D yaw, pitch, roll

Estimating yaw, pitch, roll will determine the orientation

Accelerometer equation

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} \text{Rotation} \\ \text{Matrix R} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix}$$

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} \cos(pitch) & 0 & -\sin(pitch) \\ 0 & 1 & 0 \\ \sin(pitch) & 0 & \cos(pitch) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(roll) & \sin(roll) \\ 0 & -\sin(roll) & cos(roll) \end{bmatrix} \begin{bmatrix} \cos(yaw) & -\sin(yaw) & 0 \\ \sin(yaw) & \cos(yaw) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix}$$

Accelerometer equation

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} \boxed{\text{Rotation Matrix R}} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix}$$

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} \cos(pitch) & 0 & -\sin(pitch) \\ 0 & 1 & 0 \\ \sin(pitch) & 0 & \cos(pitch) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(roll) & \sin(roll) \\ 0 & -\sin(roll) & cos(roll) \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix}$$

Accelerometer output does not depend on yaw!

Hence, yaw cannot be estimated using accelerometer

Accelerometer equation

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} \boxed{\text{Rotation Matrix R}} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix}$$

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} -\sin(pitch)\,.\cos(roll)\,.\,g \\ -\sin(roll)\,.\,g \\ -\cos(pitch)\,.\cos(roll)\,.\,g \end{bmatrix}$$

The above equations estimate pitch and roll

Magnetometer equation

$$\begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} = \begin{bmatrix} \boxed{\text{Rotation Matrix R}} \end{bmatrix} \begin{bmatrix} 0 \\ M \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} = \begin{bmatrix} \cos(pitch) & 0 & -\sin(pitch) \\ 0 & 1 & 0 \\ \sin(pitch) & 0 & \cos(pitch) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(roll) & \sin(roll) \\ 0 & -\sin(roll) & cos(roll) \end{bmatrix} \begin{bmatrix} \cos(yaw) & -\sin(yaw) & 0 \\ \sin(yaw) & \cos(yaw) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ M \\ 0 \end{bmatrix}$$

Magnetometer equation

$$\begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} = \begin{bmatrix} \boxed{\text{Rotation Matrix R}} \end{bmatrix} \begin{bmatrix} 0 \\ M \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} = \begin{bmatrix} \cos(pitch) & 0 & -\sin(pitch) \\ 0 & 1 & 0 \\ \sin(pitch) & 0 & \cos(pitch) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(roll) & \sin(roll) \\ 0 & -\sin(roll) & cos(roll) \end{bmatrix} \begin{bmatrix} \cos(yaw) & -\sin(yaw) & 0 \\ \sin(yaw) & \cos(yaw) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ M \\ 0 \end{bmatrix}$$

Pitch, roll known from accelerometer

Unknown yaw can be determined from above equations

yaw, pitch, roll together determine the rotation matrix (3D orientation) of a system

Gyroscope

1D example

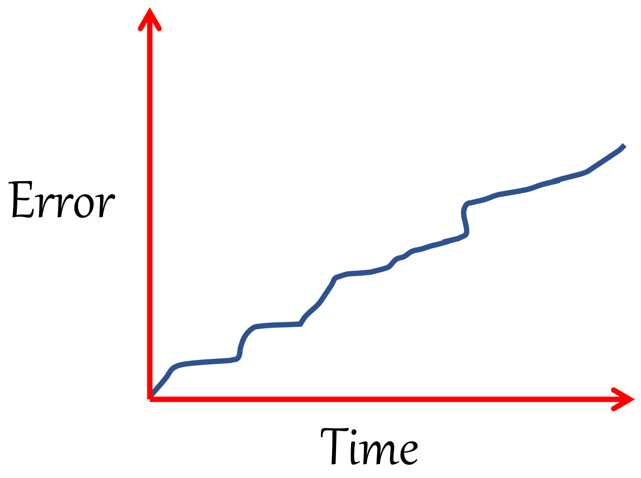
- Measures angular velocity

$$gyro = \omega$$

$$\frac{d\theta}{dt} = \omega$$

$$\frac{d\theta}{dt} = \omega + noise$$

$$\theta = \int_0^t \omega \,.dt + \int_0^t noise\,.dt$$



Error accumulates over time

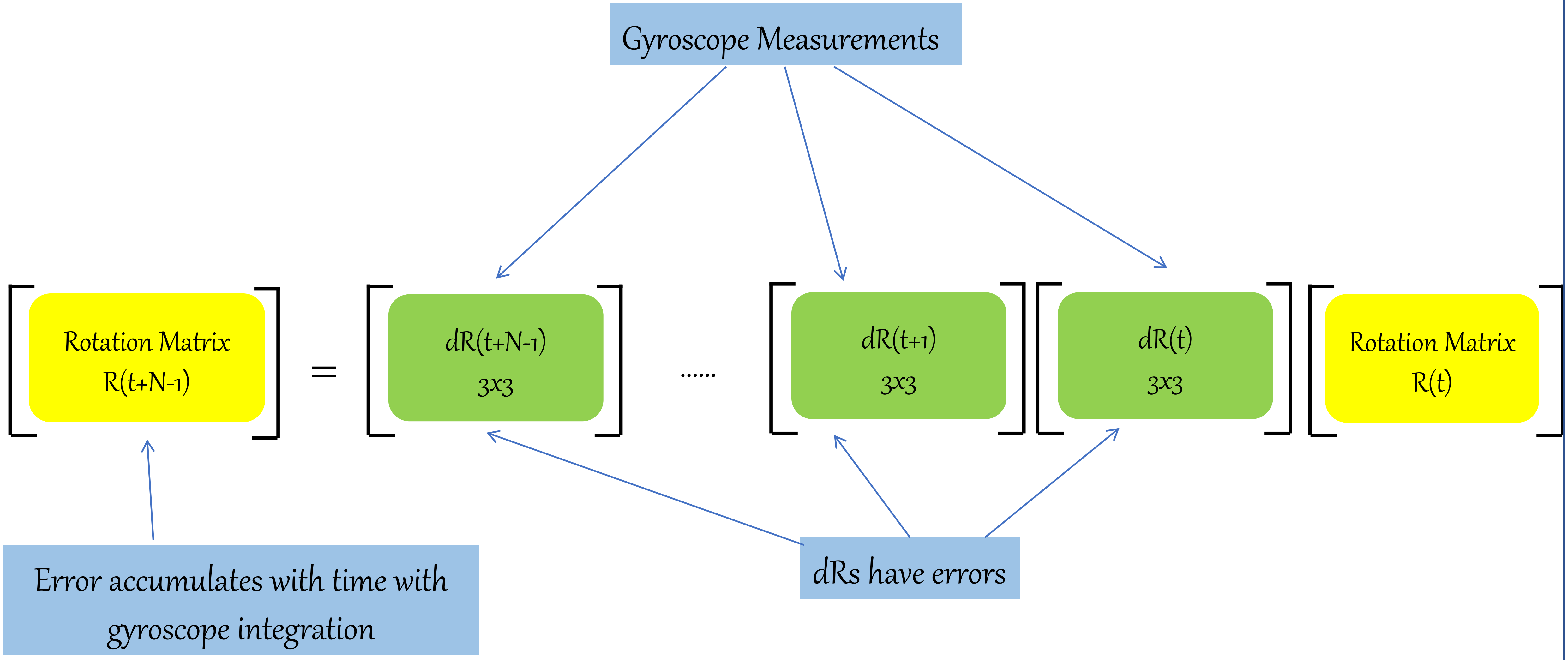
3D rotation estimation with gyroscope

3D angular velocity $\begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}$

$$\begin{bmatrix} \text{Rotation Matrix R(t+1)} \end{bmatrix} = \begin{bmatrix} \text{dR: 3x3 Matrix} \\ \text{(from Gyroscope)} \end{bmatrix} \begin{bmatrix} \text{Rotation Matrix R(t)} \end{bmatrix}$$

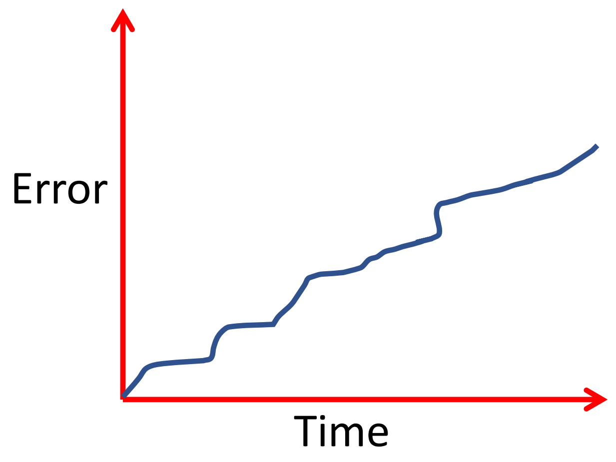
Captures relative rotation between two times

3D rotation estimation with gyroscope



Summary: two ways to measure orientation

- Using gyroscope
  - Error accumulates



- Using accelerometer and compass
  - Big advantage: No error accumulation (since there is no integration involved)
  - Accelerometer's gravity measurement can be corrupted with linear motion

$$A_{measured} = gravity + a_{motion}$$

  - Accelerometer can measure orientation only when the phone is static
  - Magnetometer is susceptible to electromagnetic interference

MECHANICAL ACTUATING SYSTEMS

WHAT WILL WE BE LEARNING?

- Types of motion
- Kinematic Chains
- Cams and Gears

WHAT IS A MECHANICAL ACTUATING SYSTEM?

- Devices which can be considered to be motion converters that is, they transform motion from one form to some other required form
  - Eg: Transform linear motion into rotational motion and vice versa.
- Mechanical elements can include the use of linkages, cams, gears, rack-and-pinion, chains, belt drives, etc.
  - Eg: rack-and-pinion can be used to convert rotational motion to linear motion.
  - Force amplification – given by levers
  - Change of speed – given by gears
  - Transfer of rotation about one axis to rotation about another – timing belt

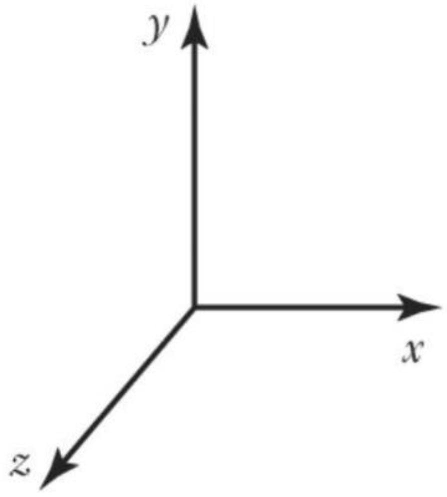
TYPES OF MOTION

Translation motion

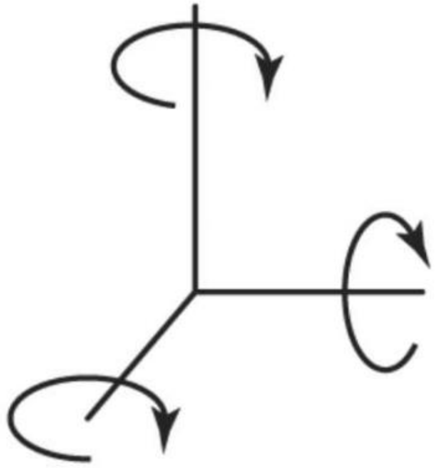
- Movement which can be resolved into components along one or more of the 3 axes.

Rotational motion

- Rotation which has components rotating about one or more of the axes.



Translation motion

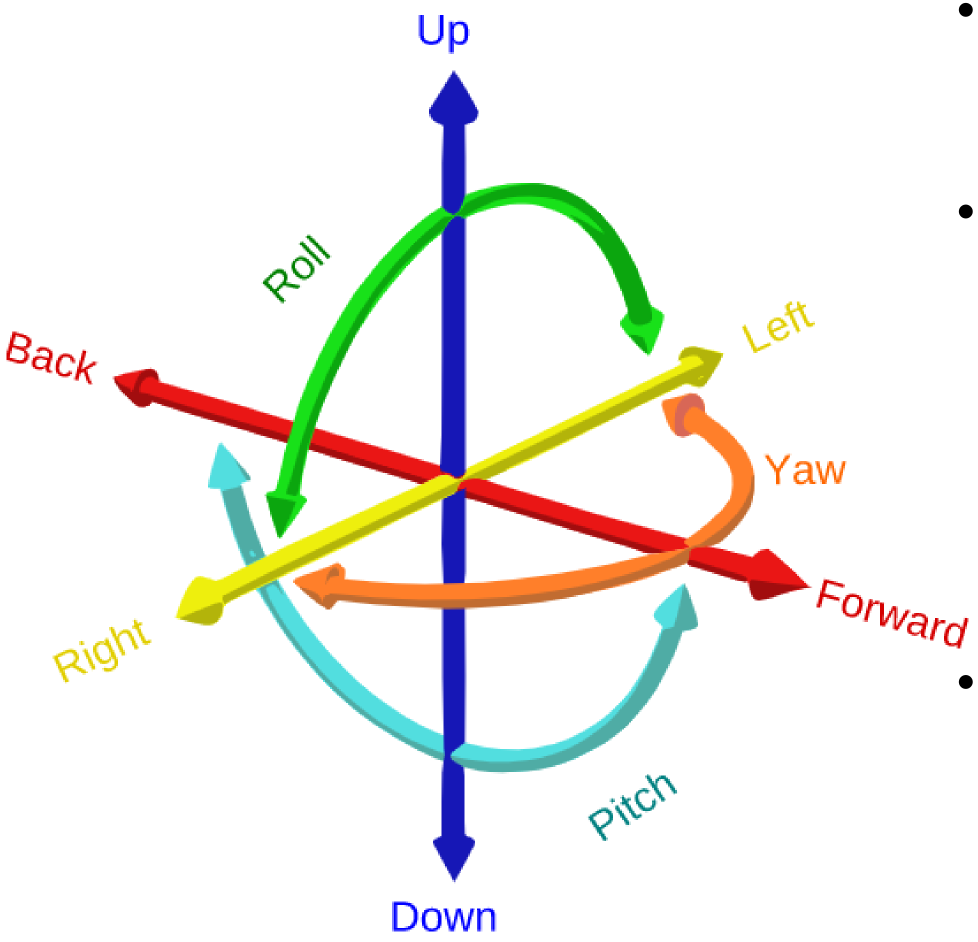


Rotational motion

DESIGN OF MECHANICAL ELEMENTS - DOF

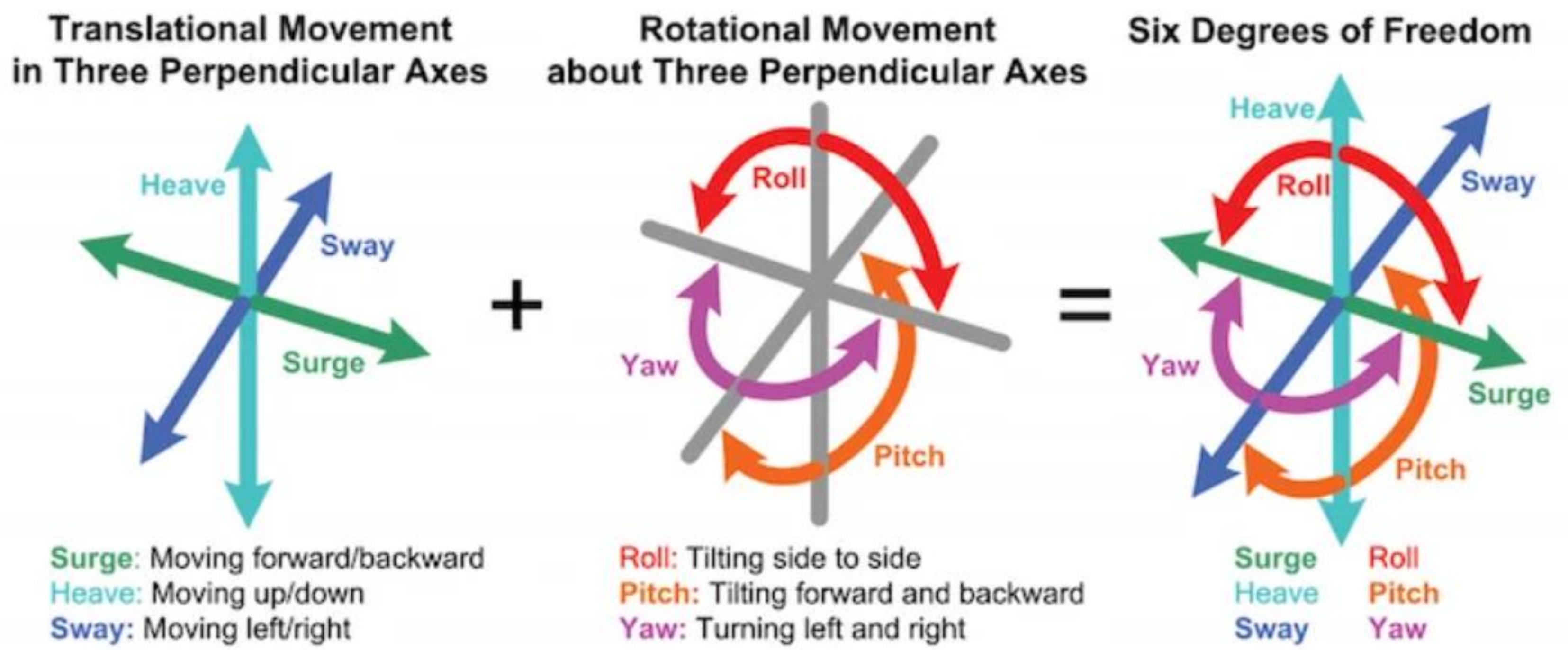
- An importance aspect in the design of mechanical elements is the orientation and arrangement of the elements and parts
- the design of a system to transmit power requires attention to the design and selection of individual components (e.g., gears, bearings, shaft)
- A body that is free in space can move in three, independent, mutually perpendicular directions and rotate in three ways about those directions.
- It is said to have six degrees of freedom (DOF).
- The number of degree of freedom is the number of components of motion that are required in order to generate the motion

WHAT ARE THE 6 DEGREES OF FREEDOM?



Translation in XYZ, and rotation in XYZ

- A point in space requires 6 independent quantities (DOF) to define its position and orientation.
- **Translational envelopes :**
  - Moving forward and backward on the X-axis. (Surge)
  - Moving left and right on the Y-axis. (Sway)
  - Moving up and down on the Z-axis. (Heave)
- **Rotational envelopes :**
  - Tilting side to side on the X-axis. (Roll)
  - Tilting forward and backward on the Y-axis. (Pitch)
  - Turning left and right on the Z-axis. (Yaw)



The translational and rotational movements that combine to form the six degrees of freedom. Image used courtesy of Honeywell

KINEMATIC CHAIN

Prerequisites

- Links
- Joints

WHAT IS A KINEMATIC CHAIN?

Kinematic chain is one in which number of links are so connected that relative motion of any point on a link with respect to any other point on the other link follows a governing law

$$L = 2/3(J+2)$$

$$J = 3/2(L)-2$$

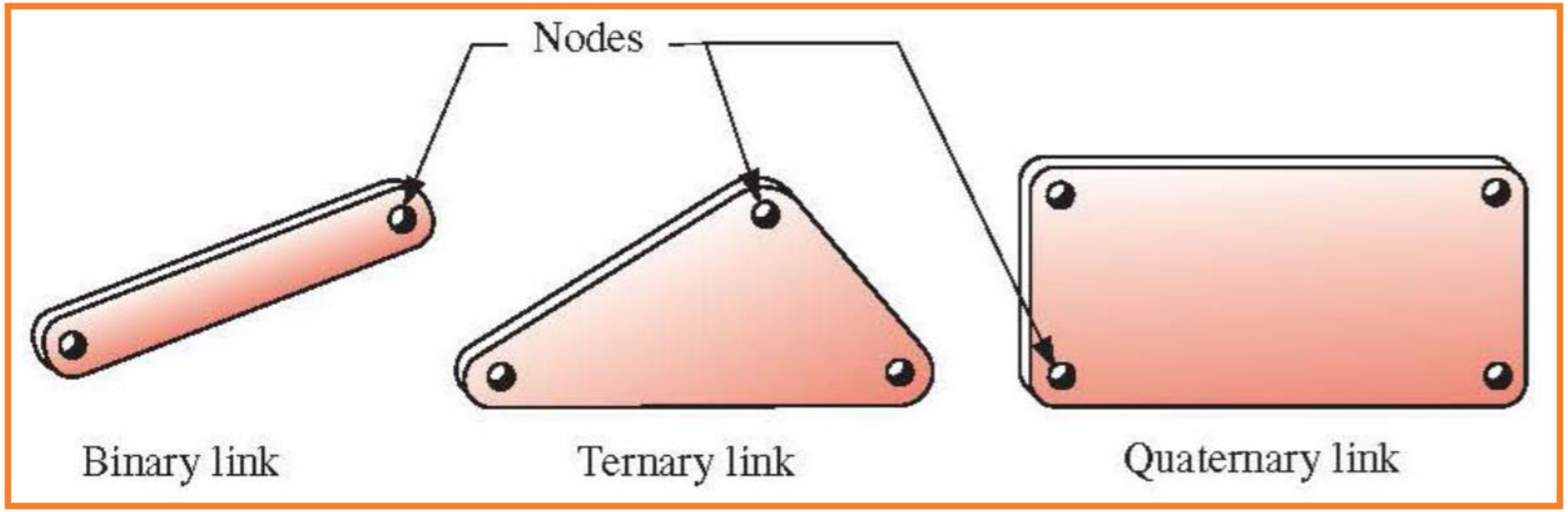
Where,

L = Number of links,

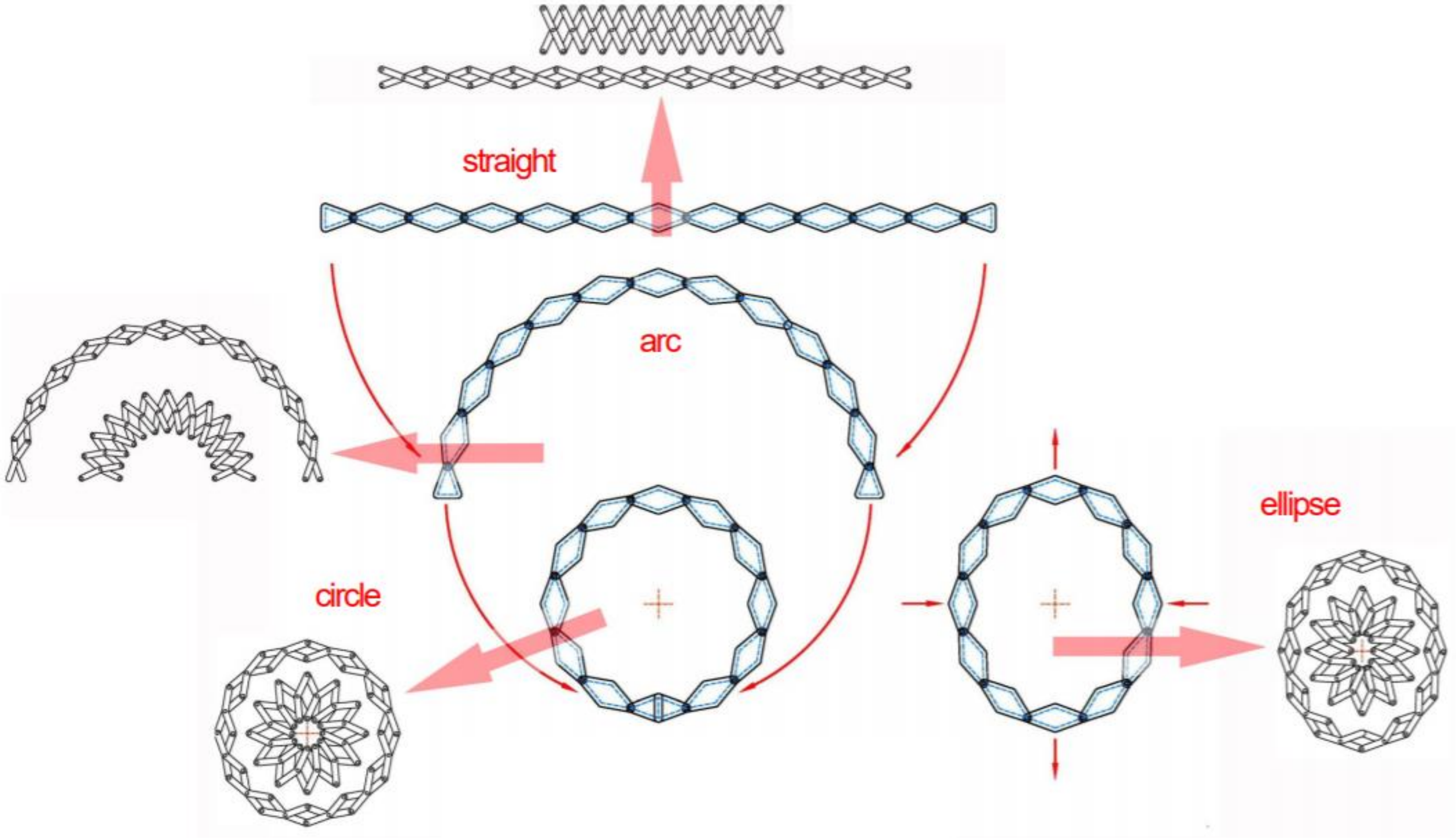
J = Number of Joints

WHAT IS A LINK?

A rigid body which possesses at least two nodes which are points of attachments to other links



‘SHAPING’ TECHNIQUE TO CREATE EXPANDING LINKAGES



WHAT IS A JOINT?

A connection between two or more links which allows some motion.

Revolute Joint allows relative rotational motion but constrains relative translation

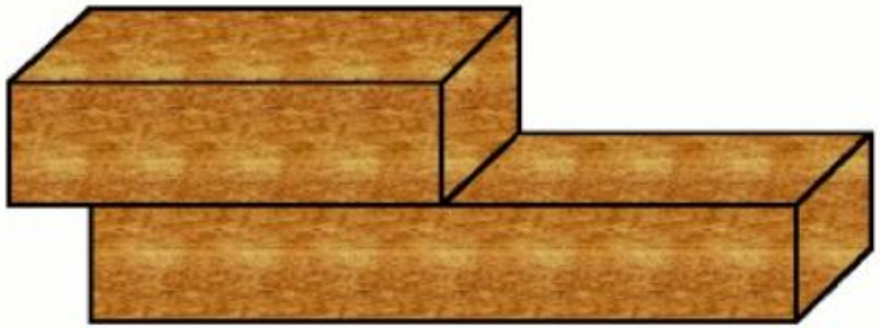
Prismatic Joint allows relative translation in one direction, but constrains relative rotation and translation in the other direction

WHAT IS A LOWER PAIR JOINT?

Lower Pair It is a pair of link which has surface to surface or area contact between members

Eg: Nut and Screw Assembly, Slider and Slotted Link

Where motion is transmitted over a surface or area

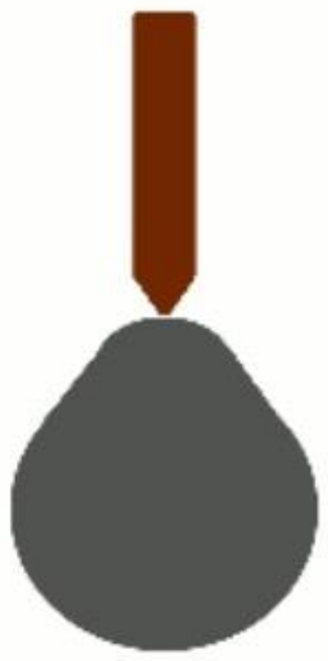


WHAT IS A HIGHER PAIR JOINT?

If a pair has point or line contact between links or member

Eg: Cam And Follower, Ball Bearing

Where motion is transmitted over a line or point



Cam & Follower

KUTZBACH CRITERIA

Kutzbach Criteria is for determining Degree of Freedom of body in Planar Mechanism (2D)

$$\boxed{DOF = 3(L-1) - 2J - H}$$

Here:

L = Number of Link

J = Number Of Lower Pair

H = Number Of Higher Pair

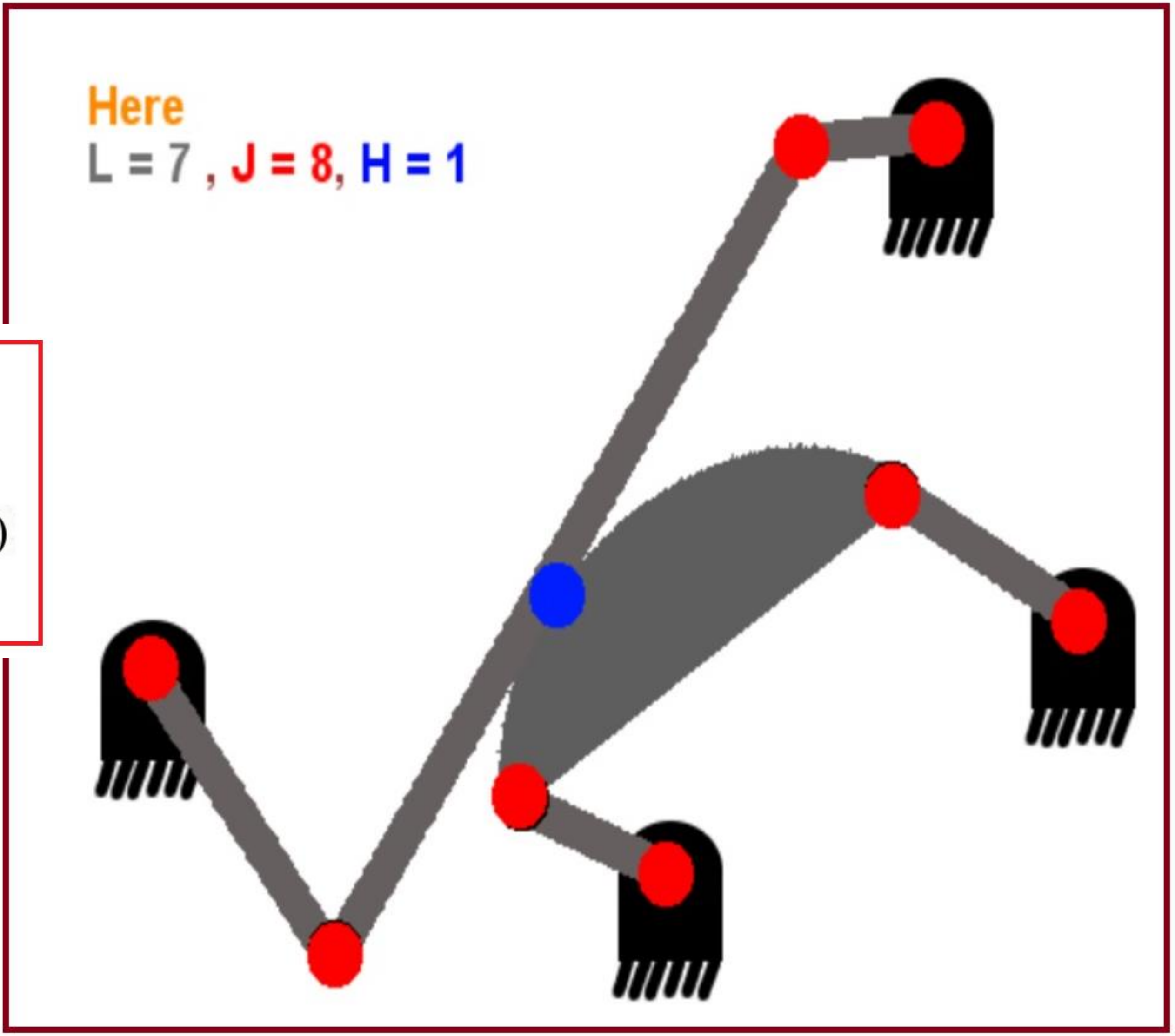
EXAMPLE

Formula

DOF = 3 (L-1) – 2 J – H

= 3 (7-1) – 2 (8) – (1)

= 1



GRUBLER'S CRITERIA

When Higher Pair (H) = 0 in Kutzbach Criteria then the Equation procured is Grubler's Criteria

$$\boxed{DOF = 3(L-1) - 2J}$$

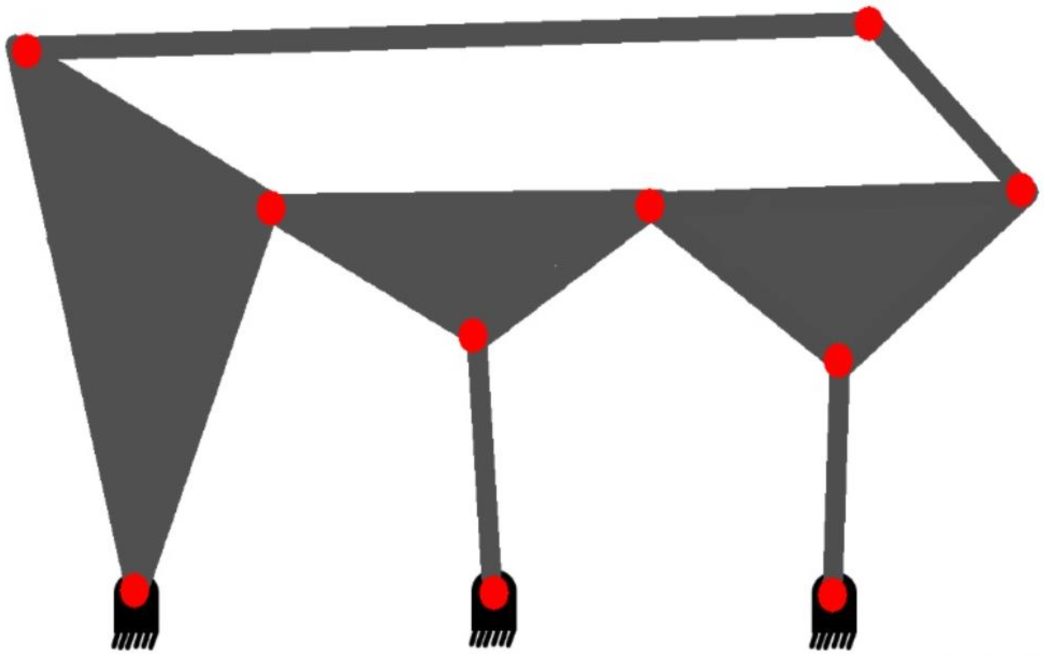
Here:

L = Number of Link

J = Number Of Lower Pair

Formula

$$DOF = 3\ (L-1) - 2\ J$$
$$= 3\ (8-1) - 2\ (10)$$
$$= 1$$



CONT…

It is possible to obtain from one kinematic chain a number of different mechanisms by having a different link as the fixed one.

The design of many mechanisms are based on two basic forms of kinematic chains

- the four-bar chain
- the slider-crank chain

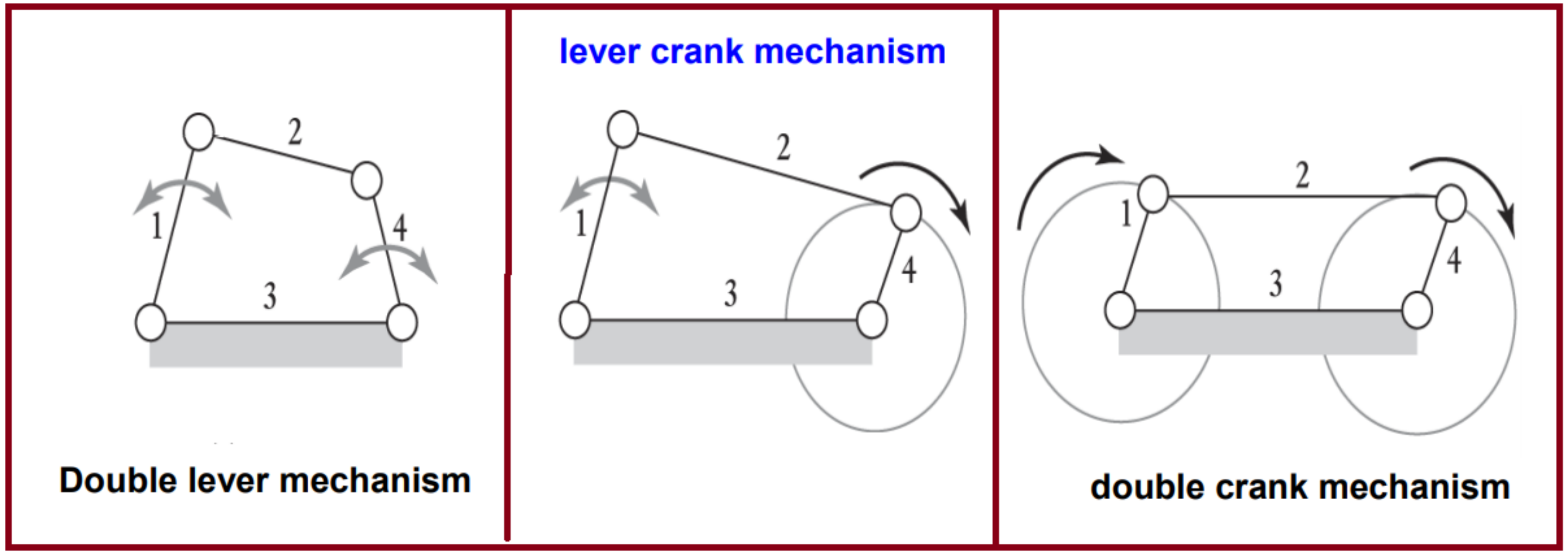
WHAT IS A 4 BAR CHAIN?

Consists of 4 links and 4 joints with two grounded points, about which turning can occur

Crank-rocker mechanism: In a four bar linkage, if the shorter side link revolves and the other one rocks (*i.e.*, oscillates), it is called a *crank-rocker mechanism*.

Double-crank mechanism: In a four bar linkage, if both of the side links revolve, it is called a *double-crank mechanism*.

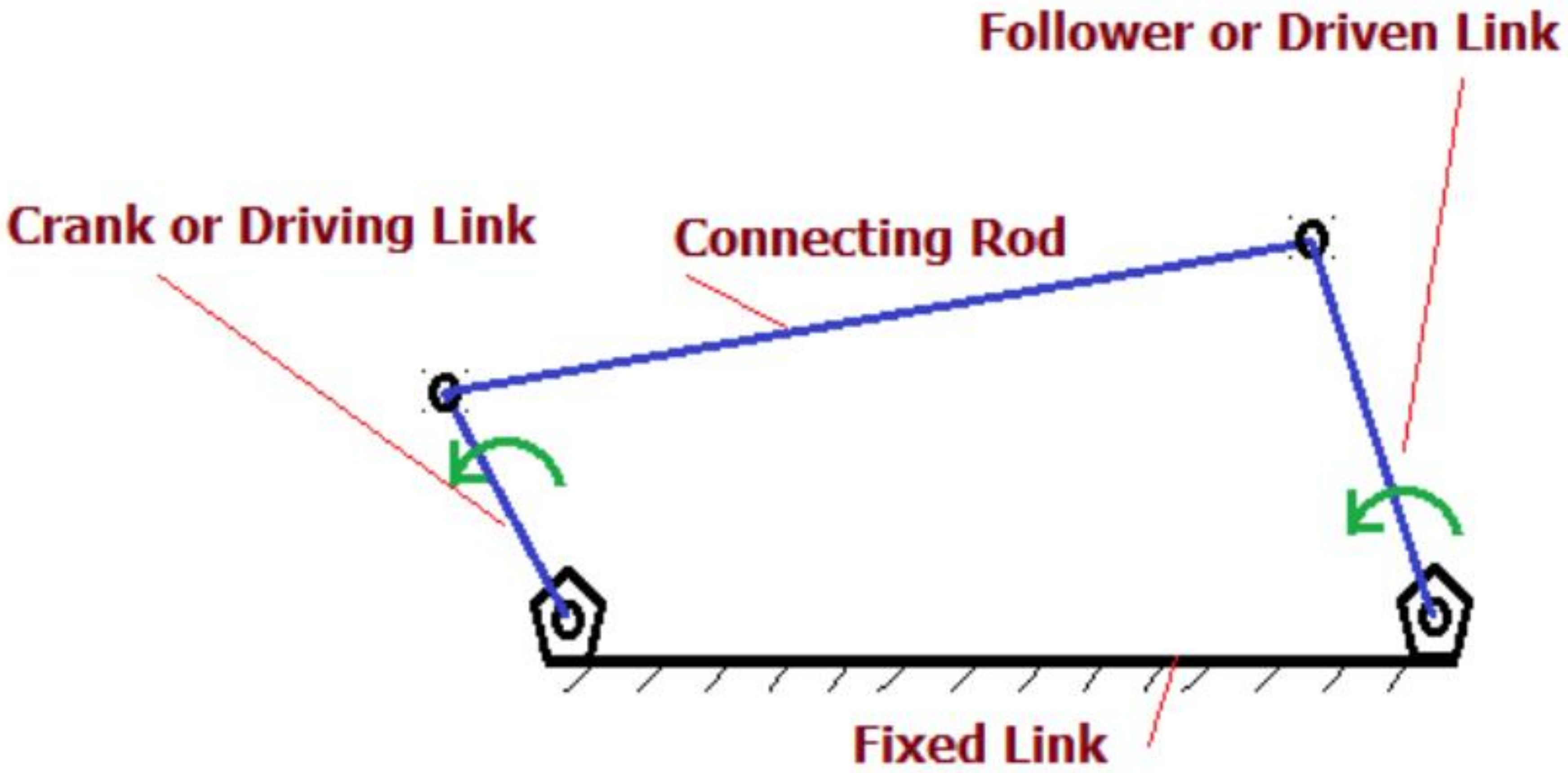
Double-rocker mechanism: In a four bar linkage, if both of the side links rock, it is called a *double-rocker mechanism*.



Double lever mechanism

lever crank mechanism

double crank mechanism



Mechanism (one link is fixed for a chain)

GRASHOF'S LAW

Determines whether continuous rotation is possible

"The sum of lengths of shortest and longest link should not be greater than the sum of the remaining link lengths if there is to be continuous relative motion between the links"

Example, Linkage mechanism of excavator and its system

$$\boxed{\Sigma(s+l) \leq \Sigma(p+q)}$$

If this is true the mechanism will rotate continuously

s = length of shortest bar
l = length of longest bar
p, q = lengths of intermediate bar

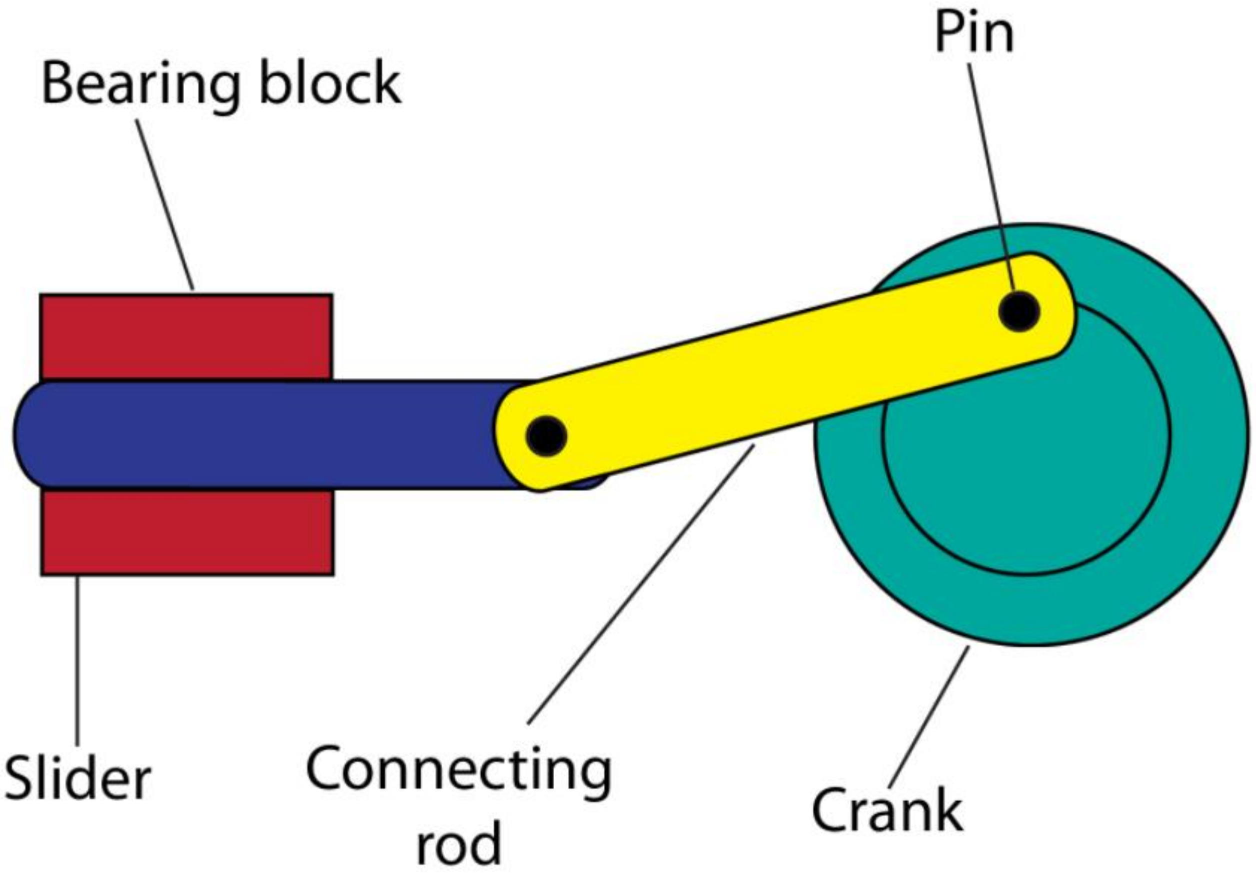
SLIDER—CRANK MECHANISM

- Converts the rotary motion of a crank to linear motion of a slider and vice versa based on application
- Circular wheel/Crank is free to rotate 360 degrees while connecting rod oscillates back and forth as one end of connecting rod attached with circular wheel/crank and another end connected to a slider which restricts it to linear motion
- Either crankshaft or slider can be the driver for this mechanism

crank -> the rotating disc

slider -> slides inside the tube

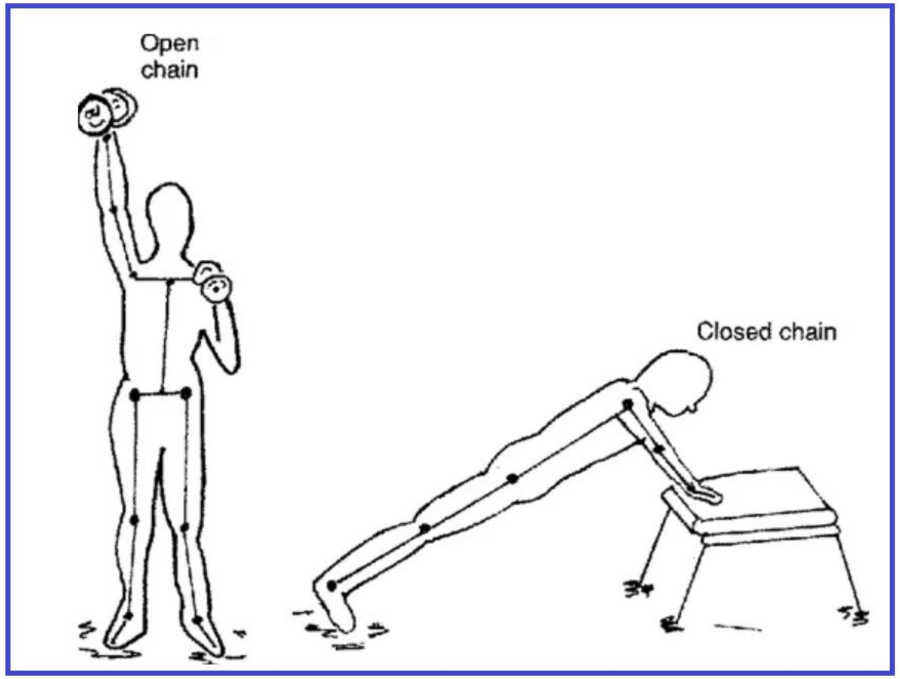
connecting rod -> joins the parts together



OPEN AND CLOSED KINEMATIC CHAIN?

Where an assembly of links and joins are connected in a way to provide a controlled output in response to an input

Closed kinematic chains restrict (or constrain) the motion of the system



THE CRITERION FOR A CHAIN TO BE CONSTRAINED:

$$J+H/2 = 3/2(L)-2,$$

Where,

H = Number of Higher pairs and

J =Number of binary joints in the chain
If R.H.S. = L.H.S.

Chain is said to be locked

VIDEOS

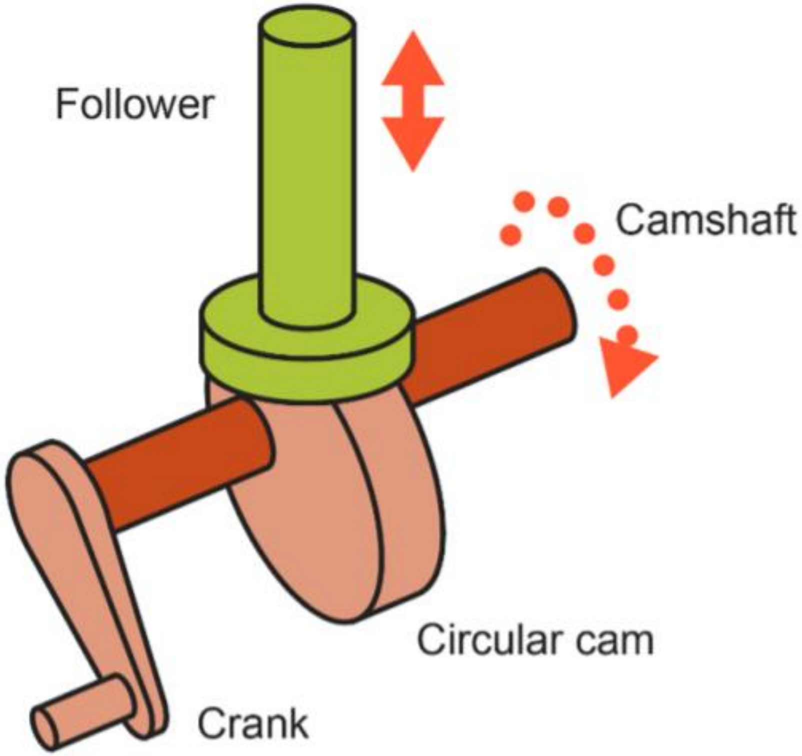
https://www.youtube.com/watch?v=3eVQA6AyE7A

https://www.youtube.com/watch?v=VHz155TZs-8

https://www.youtube.com/watch?v=3eVQA6AyE7A

CAMS AND GEARS

CAM & FOLLOWER



A cam is a mechanical device used to transmit motion to a follower by direct contact

The driver is called the cam and the driven member is called the follower

An axle or camshaft is rotated to provide movement.

Shaped pieces of material called cams are attached to the camshaft and rotated.

Followers are moved up and down along a straight path as the cam rises and falls.

WHAT IS A CAM?

A body which rotates or oscillates, and in doing so imparts a reciprocating motion to a second body - the follower.

What is the rise of a cam?

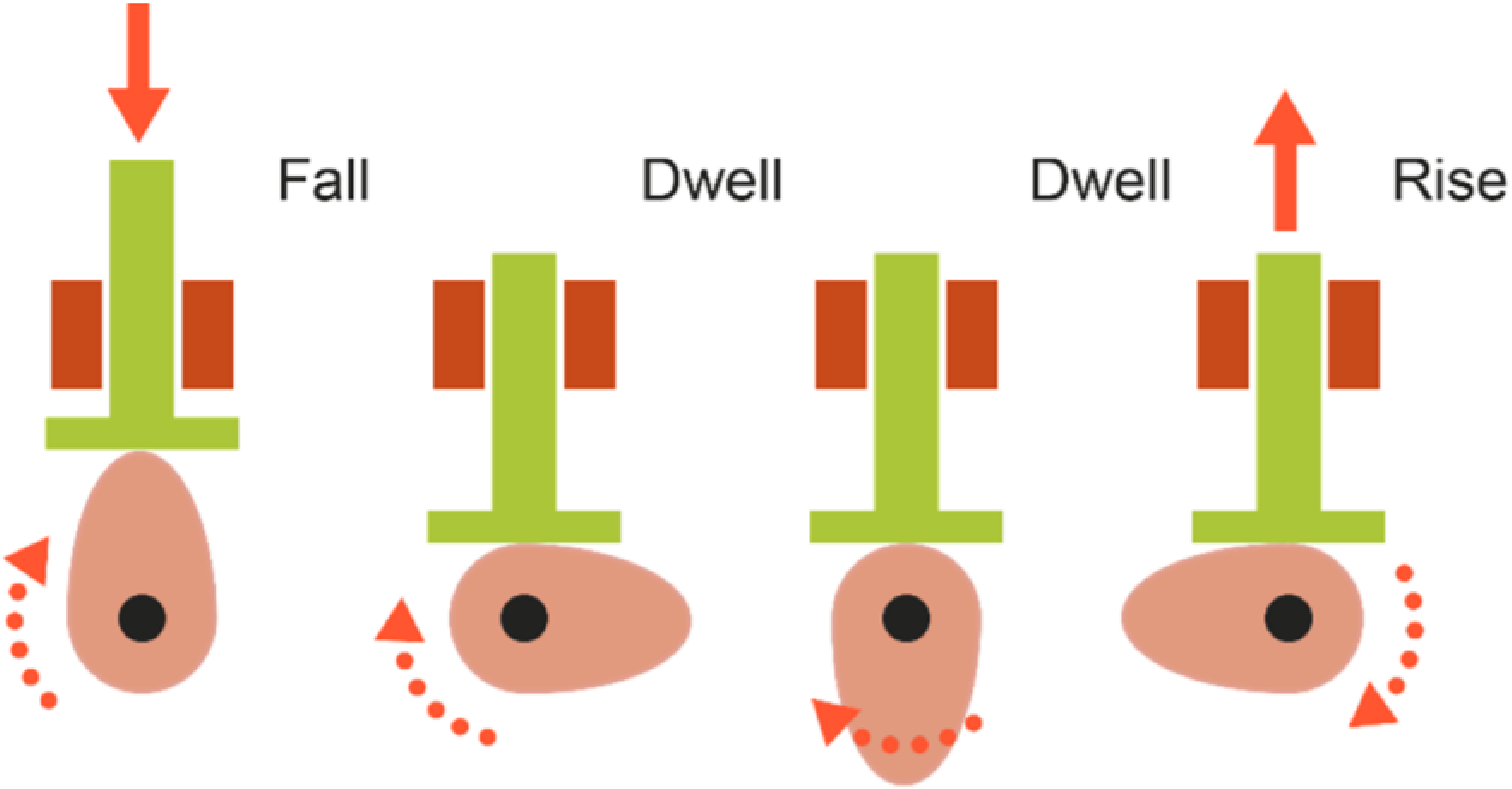
- The part that determines how quickly the follower will be lifted

What is the fall of the cam?

- The part that determines how quickly the follower will fall

What is the dwell of the cam?

- The part that allows the follower to remain at a certain height for a certain period of time



- Rise is when the follower goes up
- Fall is when the follower goes down
- Dwell is when the follower doesn’t rise or fall

TYPES OF CAM (BASED OH SHAPE)

eccentric cam

- An eccentric cam is circular shaped with an off-centre hole. It has a steady rise and fall with little dwell.

snail cam

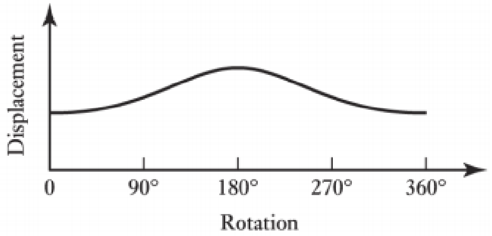
- A snail cam has a steady rise followed by a sudden fall. It has a long dwell and can only be used in one direction.

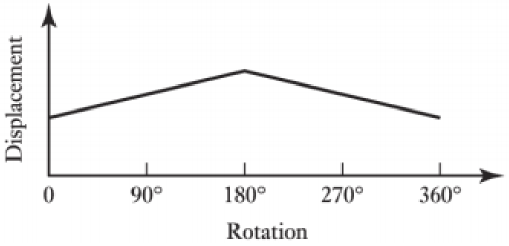
pear cam

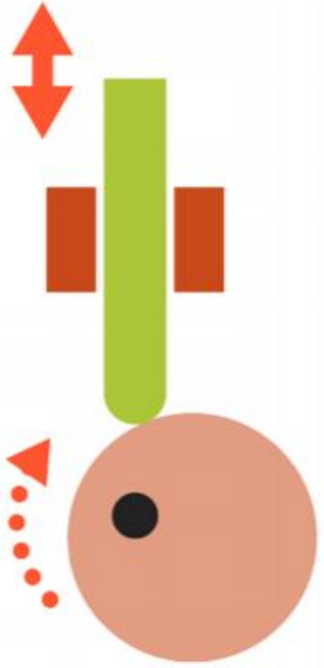
- A pear shaped cam has a rise and fall for half the rotation followed by a long dwell.

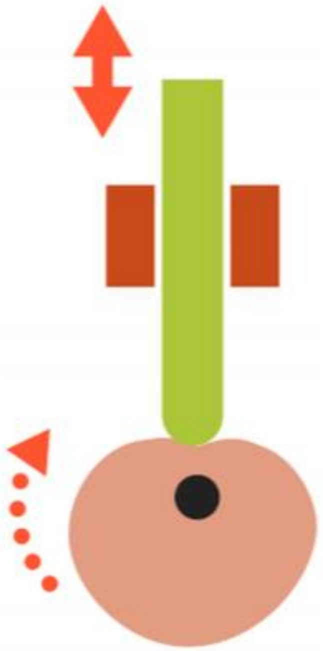
heart cam

- A heart shaped cam has smooth and gentle rise and fall. It has no dwell and is also known as a constant velocity cam.









Eccentric cam

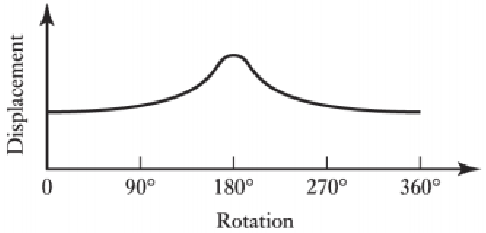
Has a steady rise and fall with little dwell.

Snail cam

Has a steady rise followed by a sudden fall. It has a long dwell. Can only be used in one direction.

Pear cam

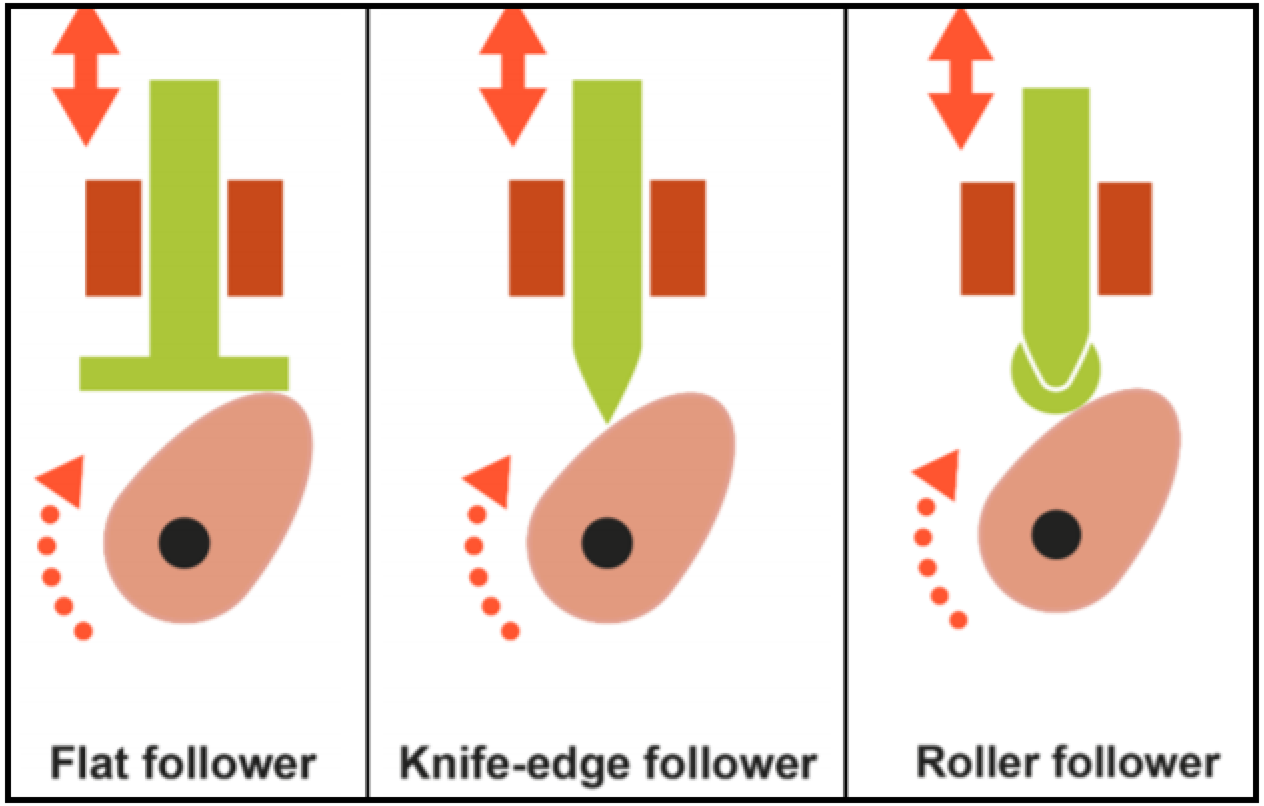
Has a rise and fall for half the rotation followed by a long dwell.



Heart cam

Has smooth and gentle rise and fall. Has no dwell. Also known as constant velocity cam.

COMMONLY USED CAM FOLLOWERS

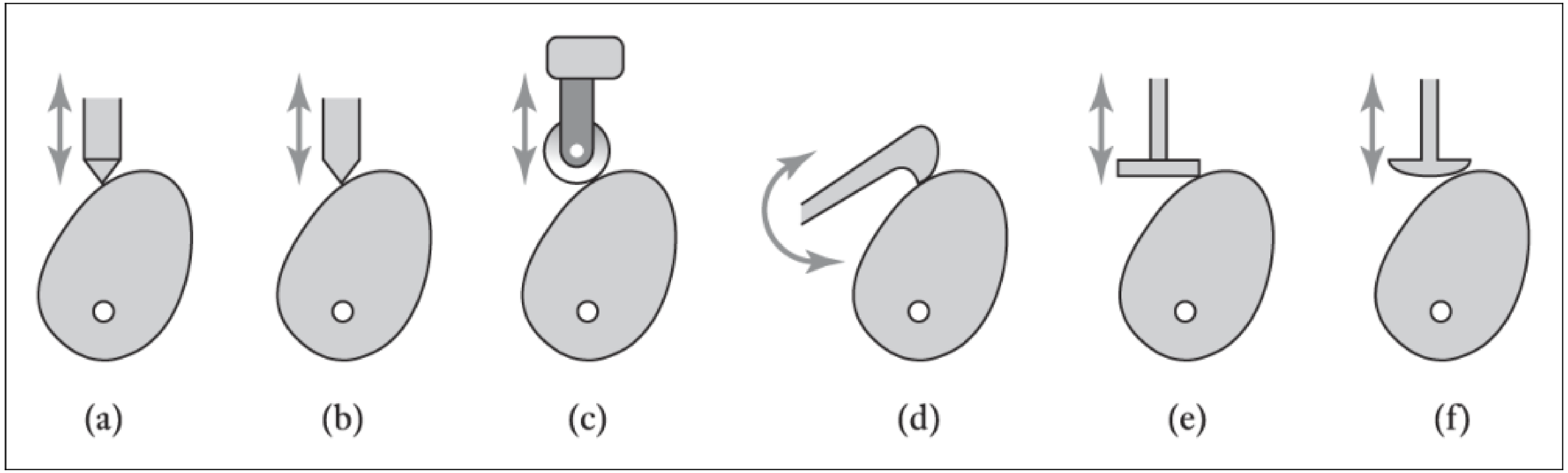


High levels of friction and are not very accurate but are good under load.

Accurately track cams and have low friction. Prone to wear on tip and not good with weight.

Track cams with some accuracy, have very low friction and are good under load. Use of bearings helps.

OTHER TYPES OF CAM FOLLOWERS



Cam followers: (a) point, (b) knife, (c) roller, (d) sliding and oscillating, (e) flat, (f) mushroom

VIDEOS

https://www.youtube.com/watch?v=Ibs10c9FX0M

https://www.youtube.com/watch?v=HsXWewecMLE

ANIMATIONS-CAM-USES

- https://technologystudent.com/cams/cam10.htm
- https://technologystudent.com/cams/snail1.htm
- https://technologystudent.com/cams/cam1.htm
- https://technologystudent.com/cams/swash1.htm

GEAR

- A circular toothed object used to transfer rotary motion and torque (a measure of how much a force acting on an object causes the object to rotate) through interlocking teeth.
- Transfer motion or power from one moving part to next
- Application - Anywhere there are engines and motors making rotational motion
- Purpose
  - Reverse direction of rotation
  - Increase or decrease speed rotation
  - Move rotational motion to a different axis
  - Keep rotation of two axis synchronized

FORMS OF GEARS

Spur Gear

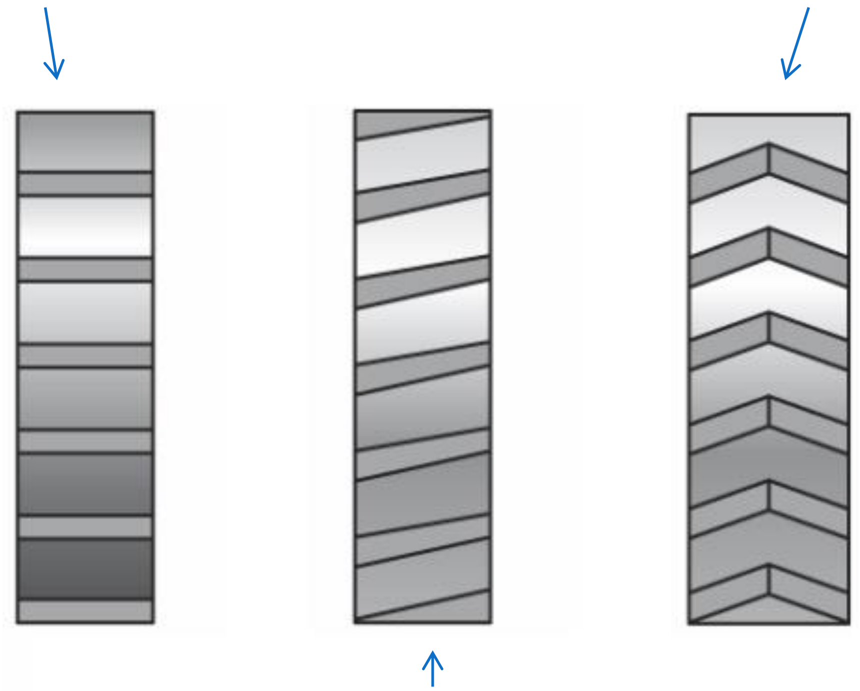
- a gearwheel with teeth projecting parallel to the wheel's axis

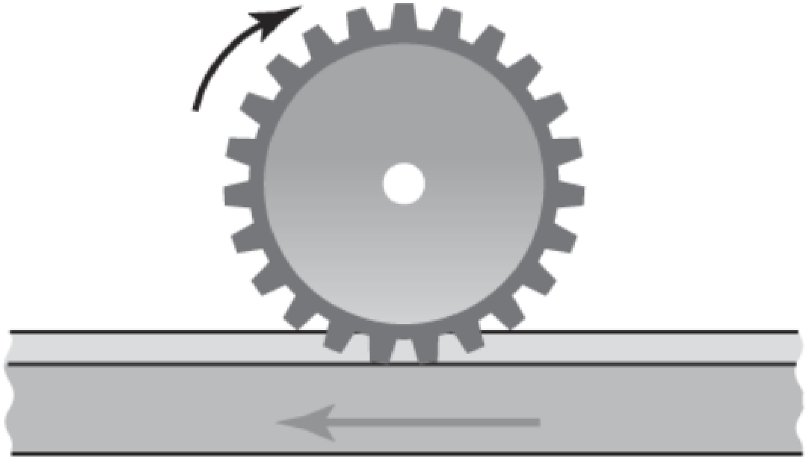
Helical gears

- helical teeth with teeth being cut on helix
- helical gears have the advantage of smoother drive and prolonged life of gears, however, the inclination of the teeth results in an axial force component on the shaft bearing which can be overcome by using double helical teeth.

Rack and Pinion

- A rotating gear that meshes with a bar that has gear teeth along its length.
- Changes rotating motion into linear motion.
- Used for big increase in torque.

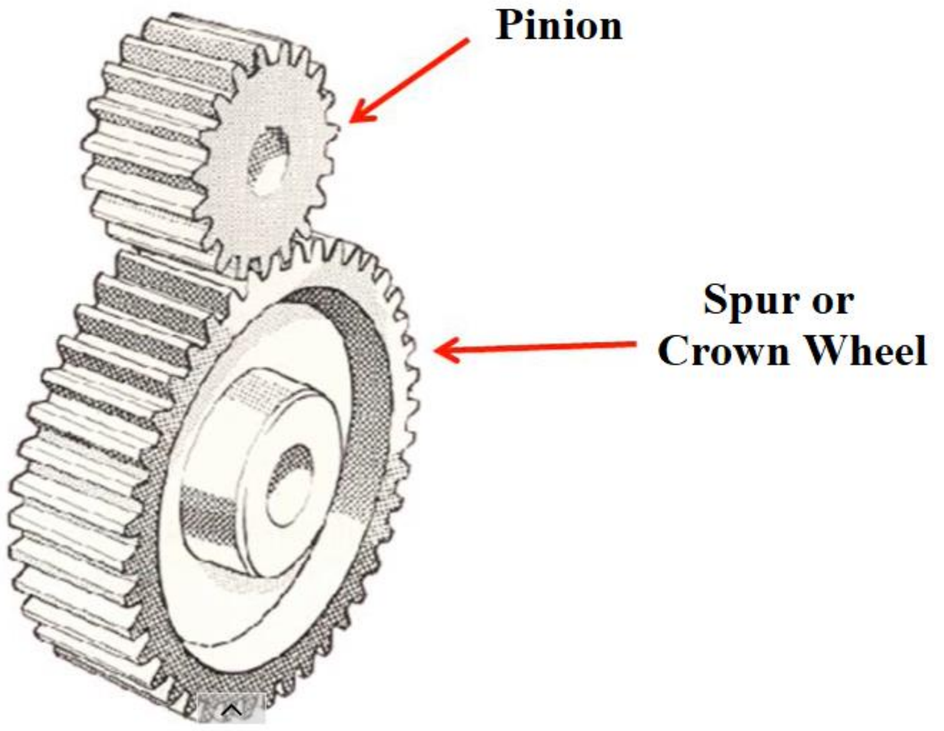




Rack and pinion

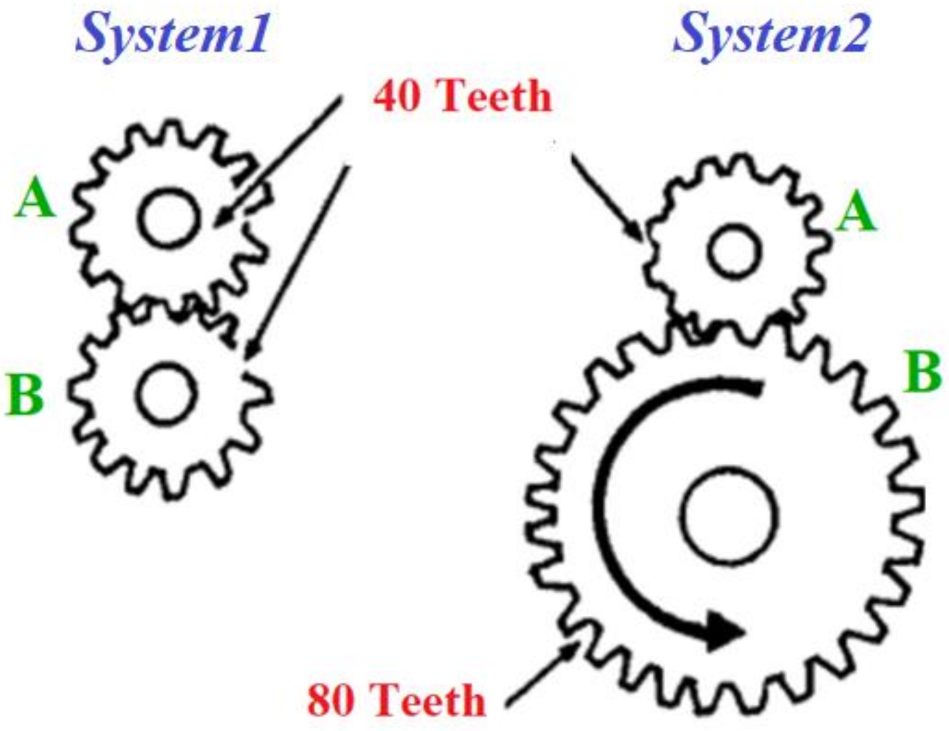
TWO MESHED GEARS

When two gears in mesh; the larger gear wheel is called the **spur** (or crown wheel), the smaller is called the **pinion**



GEARS RATIO

- Difference of speed between motor and endpoint
- Example: Consider meshed wheels A & B .
  - System1 -> A with 40 teeth and B with 40 teeth
  - System2 -> A with 40 teeth and B with 80 teeth
- Wheel B must have twice the diameter of wheel A.



- The **gear ratio** is calculated by dividing the output speed by the input speed (i= Ws/ We) or by dividing the number of teeth of the driving **gear** by the number of teeth of the driven **gear** (i= Ze/ Zs)

System1

$$\frac{\omega_A}{\omega_B}=\frac{No\ of\ teeth\ on\ B}{No\ of\ teeth\ on\ A}=\frac{40}{40}$$

$$\omega_A=\omega_B$$

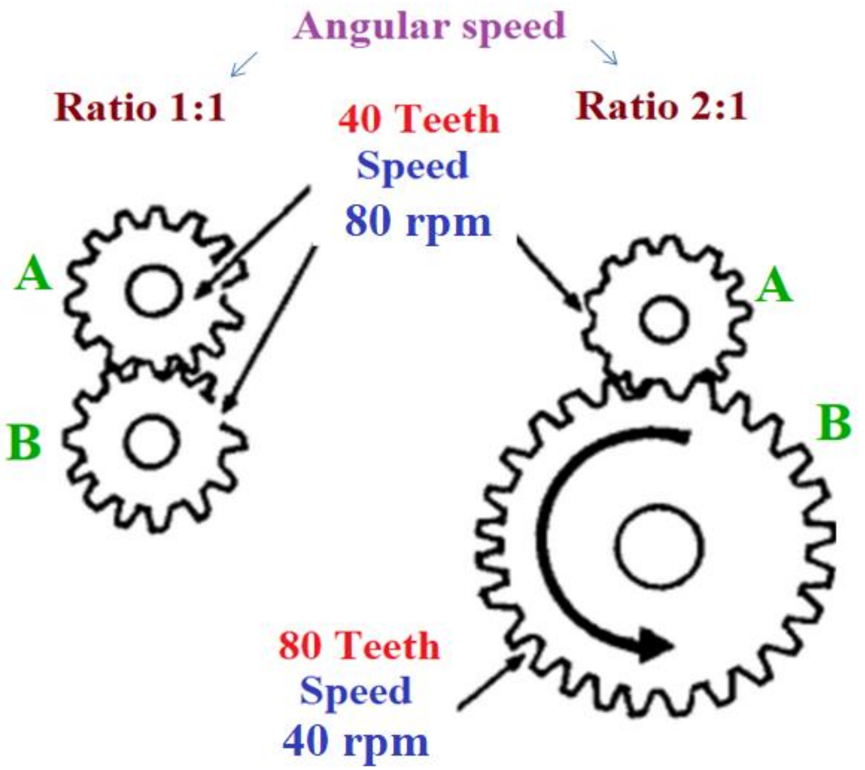
$$\boxed{G=\frac{\omega_A}{\omega_B}=\frac{d_B}{d_A}=gear\ ratio=1}$$

System2

$$\frac{\omega_A}{\omega_B}=\frac{No\ of\ teeth\ on\ B}{No\ of\ teeth\ on\ A}=\frac{80}{40}=2$$

$$\omega_A=2\omega_B$$

$$\boxed{G=\frac{\omega_A}{\omega_B}=\frac{d_B}{d_A}=gear\ ratio=2}$$



Number of teeth /Diameter -> gives gear ratio

GEAR TRAIN

A connected set of rotating gears that transmits power from an input to an output

A group of 2 or more gears meshed together to transfer power

Two attributes that can be controlled by gear train

- Speed
- Torque

SIMPLE GEAR TRAIN

Driving gear

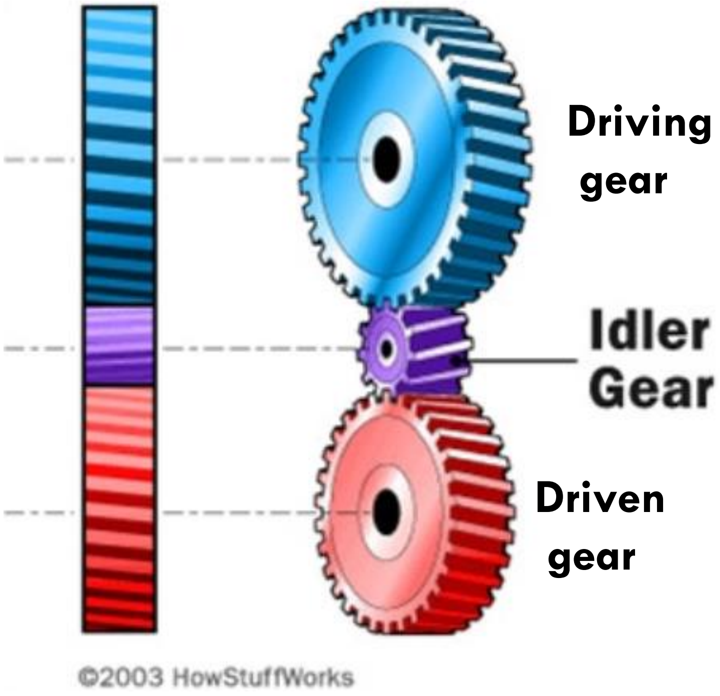
- input gear
- The gear that supplies force to another gear/connected to input

Driven Gear

- output gear / Follower gear
- The member of a pair of gears to which motion and power are transmitted by the other. The output gear

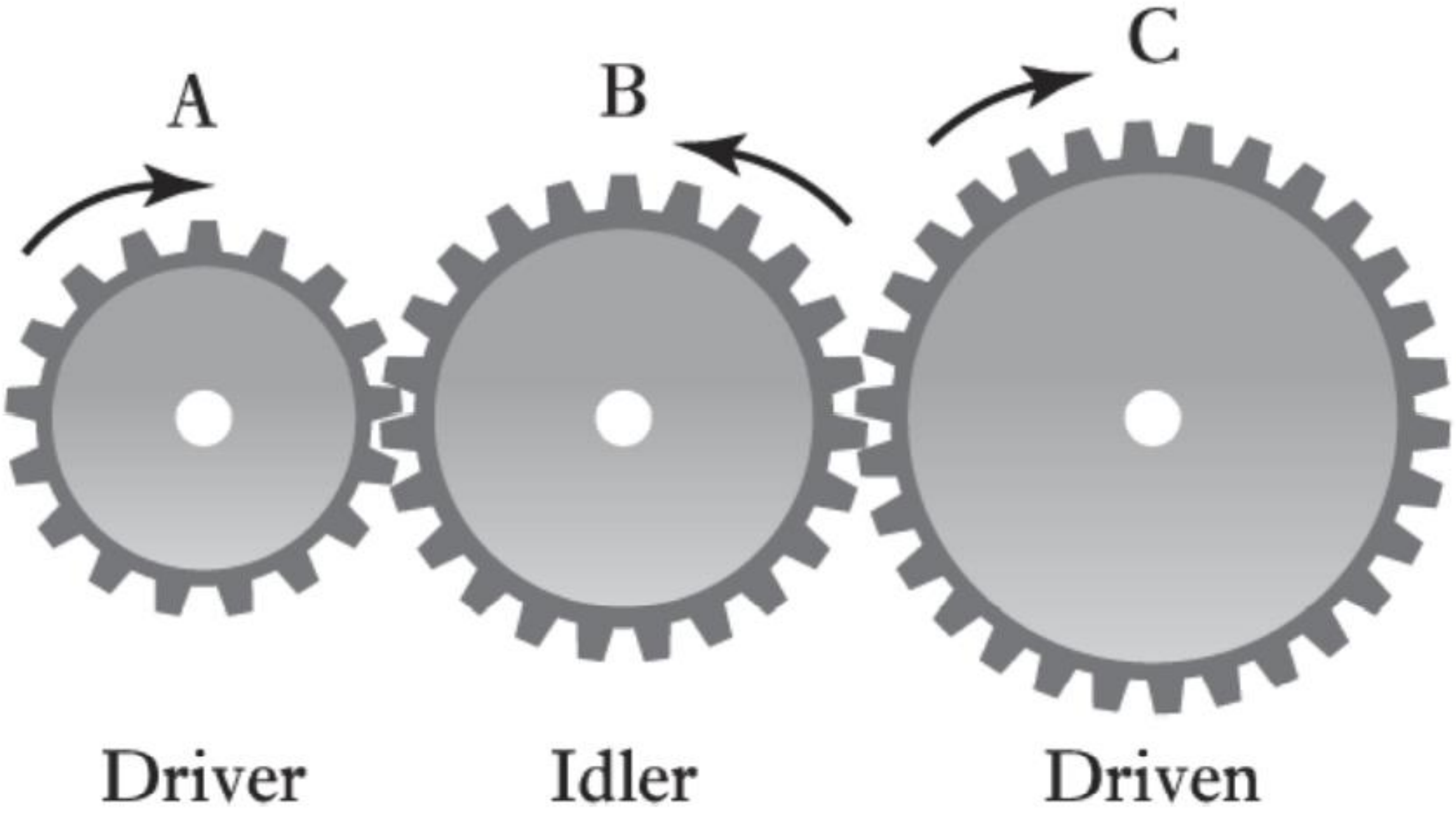
Idler gear

- A gear between the driver and the driven gear used to change rotational direction



Formula

$$\text{Gear ratio} = \frac{\text{Driven teeth}}{\text{Driver teeth}}$$



$$\boxed{G = \frac{\omega_A}{\omega_C} = \frac{\omega_A}{\omega_B} \times \frac{\omega_B}{\omega_C}}$$

COMPOUND GEAR TRAIN

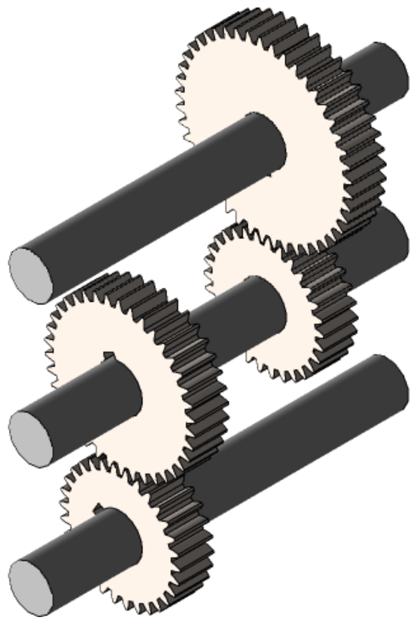
This term is used to describe a gear train when two (or more) wheels are mounted on a common shaft.

(or)

An assembly of two gears of different sizes, fixed to a single axle.

Also called a stacked gear.

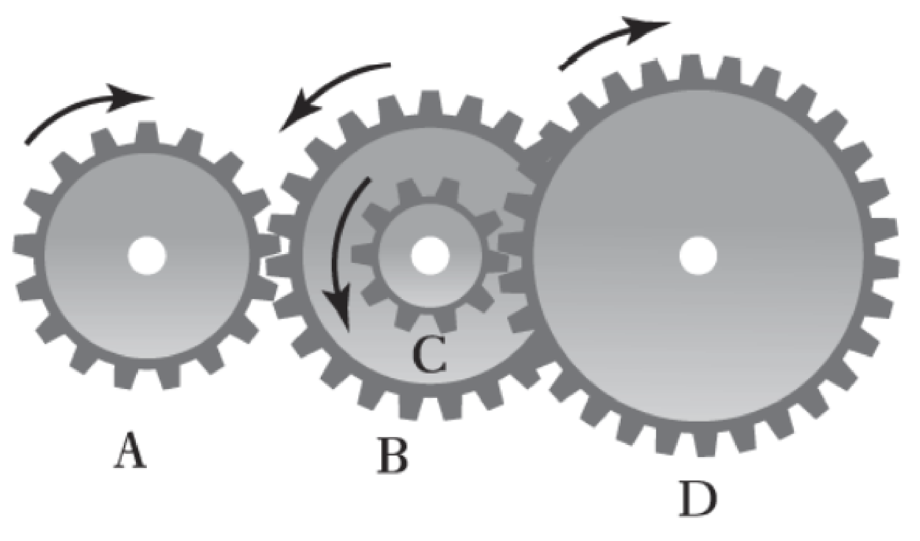
When two wheels are mounted on the same shaft, they have the same angular velocity.

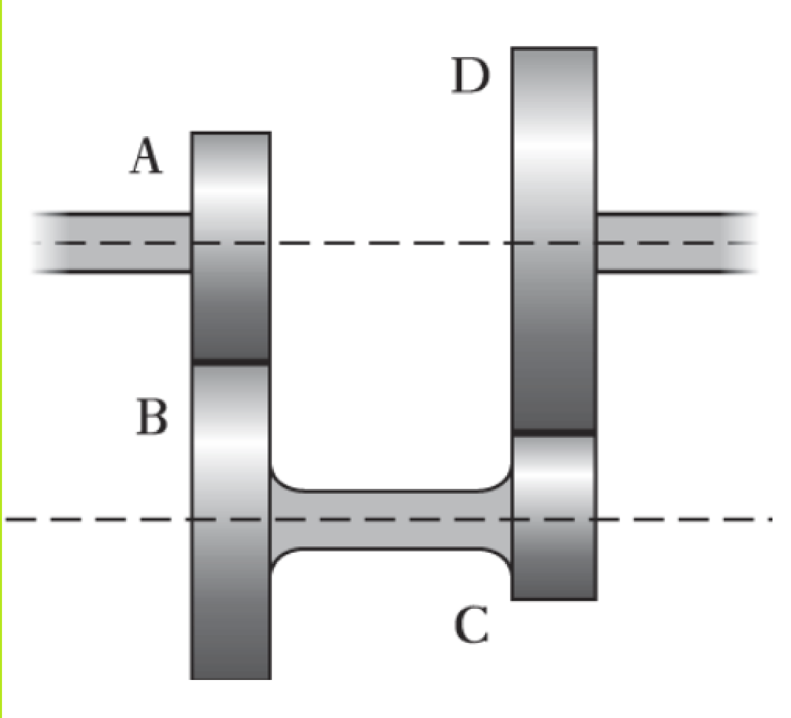


$$\boxed{\omega_B = \omega_C}$$

The over all gear ratio

$$\boxed{G = \frac{\omega_A}{\omega_D} = \frac{\omega_A}{\omega_B} \times \frac{\omega_B}{\omega_C} \times \frac{\omega_C}{\omega_D} = \frac{\omega_A}{\omega_B} \times \frac{\omega_C}{\omega_D}}$$





For the input and output shafts to be in line

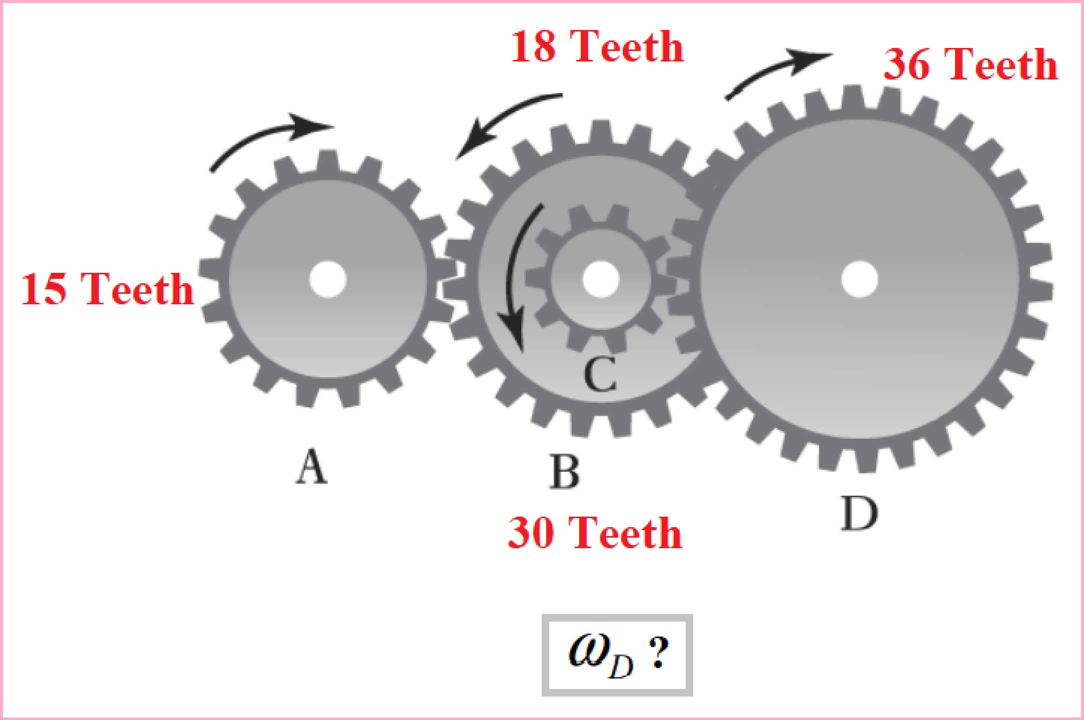
$$\boxed{d_A + d_B = d_C + d_D}$$

Example:

If A has 15 teeth, B 30 teeth, C 18 teeth and D 36 Teeth. Find the angular speed of D if A speed is 160 rpm

Sol:

Since the angular speed of a wheel is inversely proportional to the number of teeth on the wheel, the overall gear ratio is



$$G = \frac{30}{15} \times \frac{36}{18} = 4 = \frac{\omega_A}{\omega_D}$$

$$\boxed{\omega_D = \frac{\omega_A}{4} = 160/4 = 40 \ rpm}$$

VIDEO

https://www.youtube.com/watch?v=ihGFUAAwj7g

https://www.youtube.com/watch?v=BKjo8Usp21k

PNEUMATIC AND HYDRAULIC ACTUATING SYSTEMS

INTRODUCTION

- Use pressurized fluid to transmit power

What are the 2 fluids?

- liquids (hydraulics)
- gas (pneumatics)

- The Hydraulic fluid power system is usually selected when an application requires a high operating pressure.

- The Pneumatic fluid power system can usually provide the best solution where lightweight and easily handled tools are a requirement.

- Hydraulic/Pneumatic Amplifying Elements employing various types of valves or constrictions, to get significant variation in pressure with small variation in the input parameters

COMPARISON

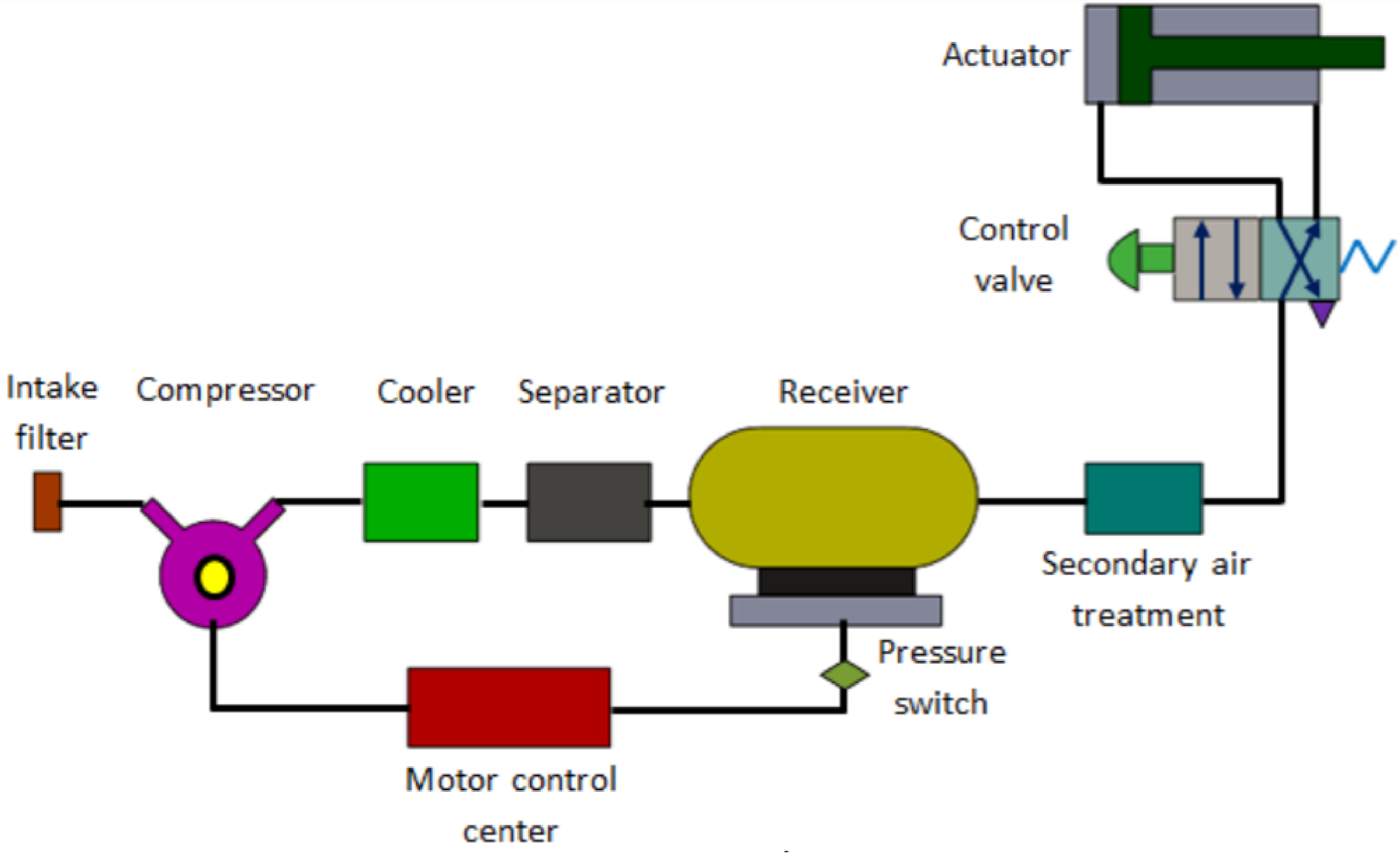
S. No.	Hydraulic System	Pneumatic System
1.	It employs a pressurized liquid as a fluid	It employs a compressed gas, usually air, as a fluid
2.	An oil hydraulic system operates at pressures up to 700 bar	A pneumatic system usually operates at 5–10 bar
3.	Generally designed as closed system	Usually designed as open system
4.	The system slows down when leakage occurs	Leakage does not affect the system much
5.	Valve operations are difficult	Valve operations are easy
6.	Heavier in weight	Lighter in weight
7.	Pumps are used to provide pressurized liquids	Compressors are used to provide compressed gases
8.	The system is unsafe to fire hazards	The system is free from fire hazards
9.	Automatic lubrication is provided	Special arrangements for lubrication are needed

PNEUMATIC ACTUATORS

- It converts energy, in the form of compressed air into mechanical motion
- Consists of a piston on a diaphragm
- Main principle – Has a cylinder, keeps the air in the upper portion, allowing air pressure to force the diaphragm/piston to create the mechanical movement. (usually opening/closing of a valve)

1. CYLINDER

- Double acting (air actuation of movement in both directions) or spring return
- In either case, the valve controlling the cylinder must provide an exhaust route for air trapped within the cylinder, to be released in the atmosphere.
- Force F exerted by the air is F = p x A.
- Friction must be subtracted from this
- The typical max operating speed of a cylinder for pneumatic actuation is 2 m/s


Actuator
Control valve
Intake filter
Compressor
Cooler
Separator
Receiver
Secondary air treatment
Pressure switch
Motor control center

COMPONENTS OF A PNEUMATIC SYSTEM

Air filters: filter out the contaminants from the air

Compressor: generates Compressed air. Air compressors are either diesel or electrically operated.

Air cooler: Reduces air temperature which was increased during compression operation

Dryer: water vapor or moisture in the air is separated from the air

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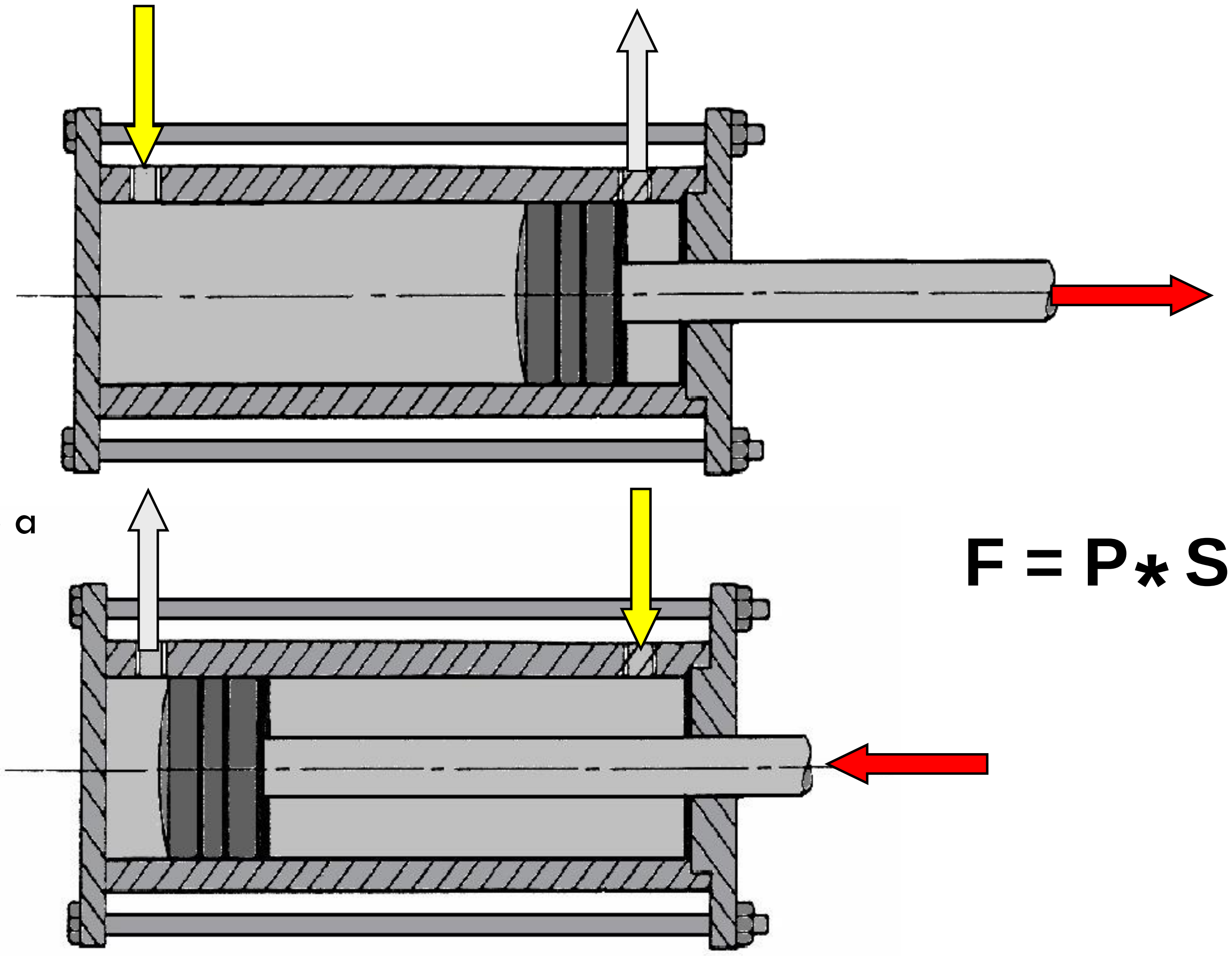
Control Valves: used to regulate, control and monitor for control of direction flow, pressure etc.

Air Actuator: Air cylinders and motors are used to obtain the required movements of mechanical elements of pneumatic system.

Electric Motor: Transforms electrical energy into mechanical energy. It is used to drive the compressor.

Receiver tank: The compressed air coming from the compressor is stored in the air receiver

Double effect pneumatic cylinders



double acting-air actuation of movement in both directions or have a spring return

$$F = P * S$$

Double-acting cylinders are able to produce force in both directions by applying pneumatic fluid pressure to either side of the piston

WHAT ARE DIFFERENT TYPES OF DOUBLE-ACTING CYLINDERS?

double-rod cylinders

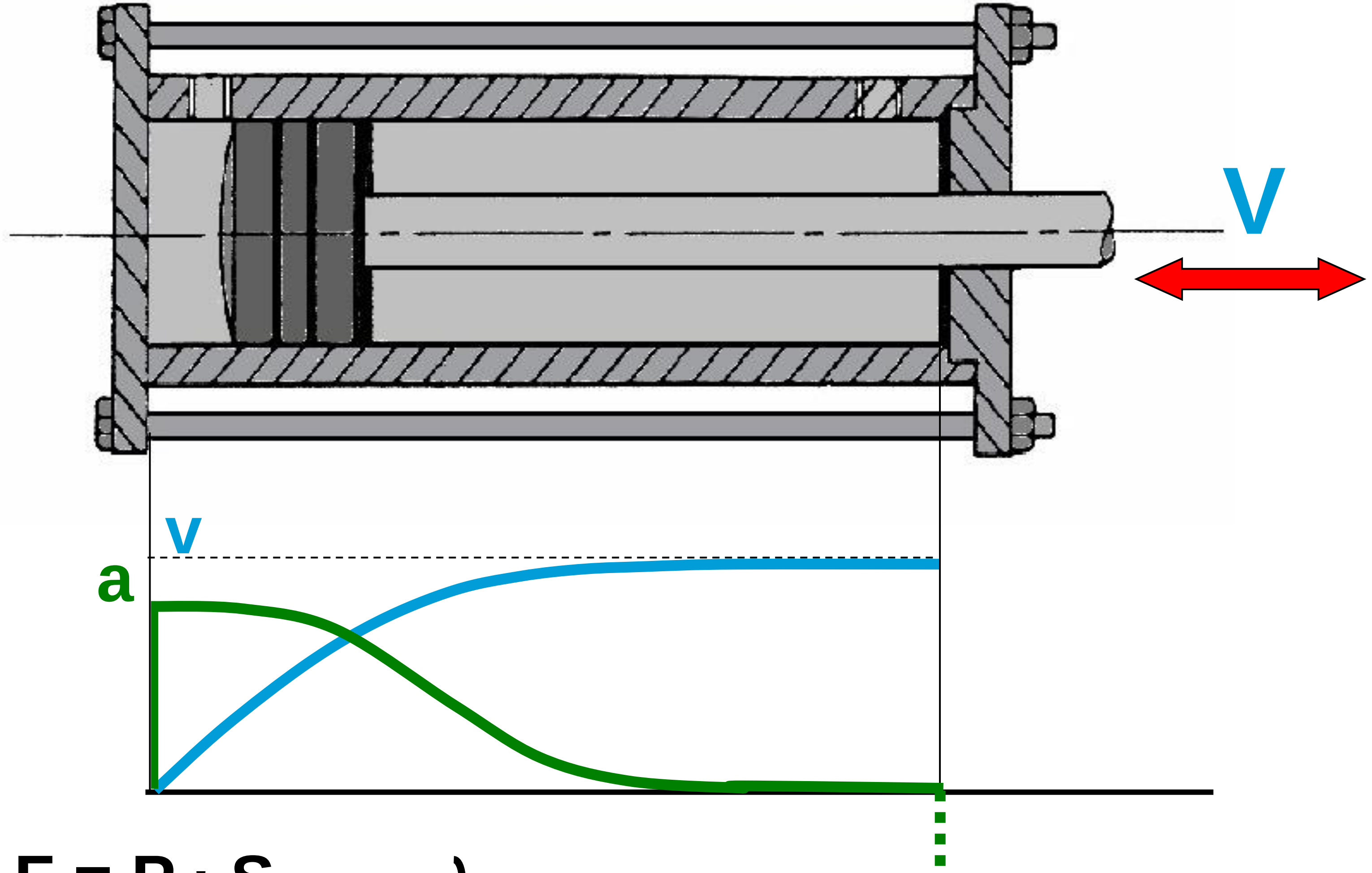
- a hydraulic cylinder that has a single piston and rod that protrudes from both end caps of the cylinder

tandem cylinders

- a hydraulic cylinder that consists of two or more in-line cylinders with their rods connected to form a common rod

duplex cylinders

- a hydraulic cylinder that consists of two or more in-line cylinders that do not have their rods connected to form two or more cylinders in one housing



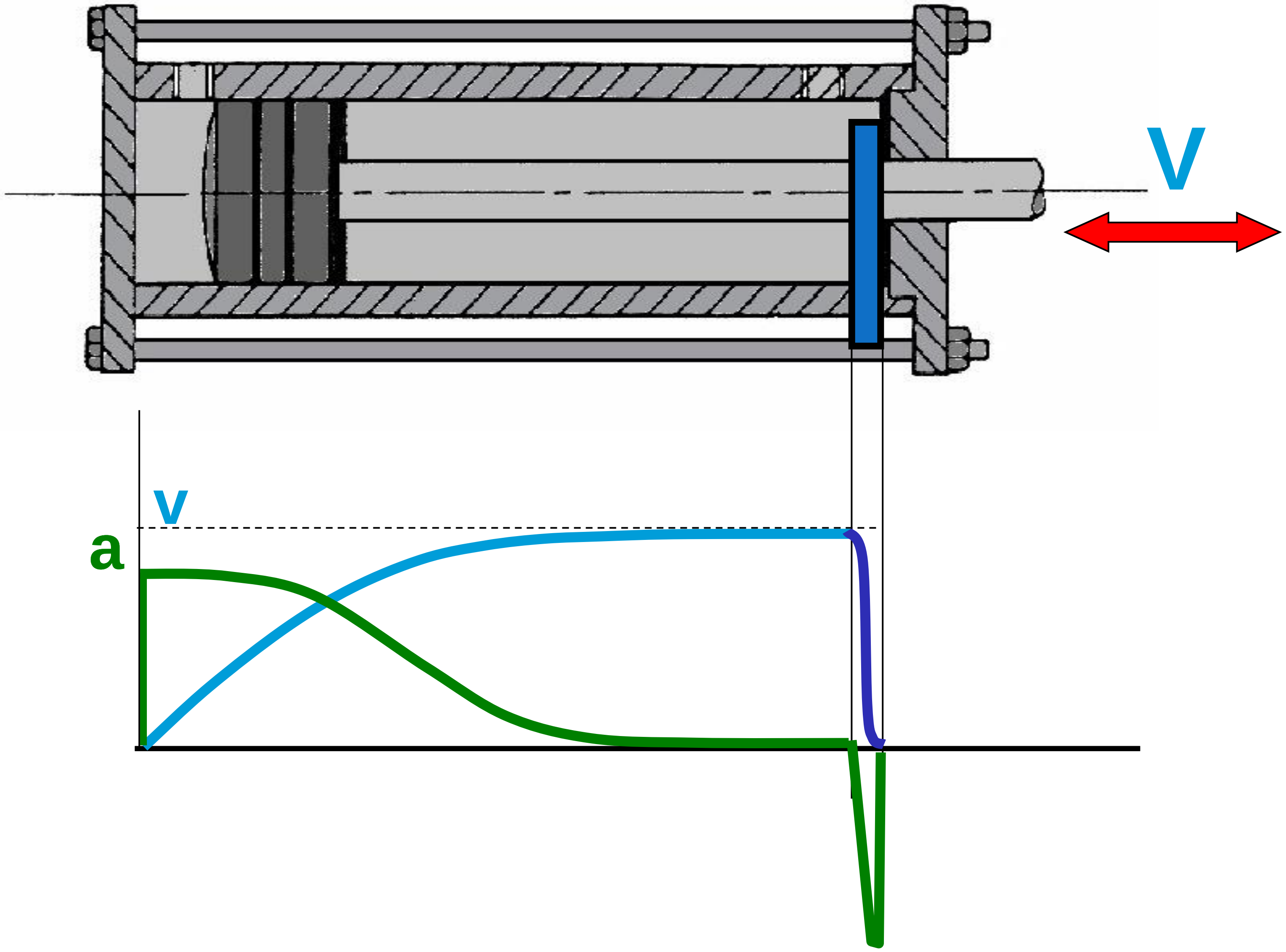
$$F = P * S$$

$$F - F_f = M * a$$

$$F_f = k * v^2$$

$$\Rightarrow \quad a = \frac{P * S - k * v^2}{M}$$

Speed is not controllable. The cylinder maximum speed is achieved when friction forces (kv^2) equal those that produce the advancing movement (F = P.S), and a = 0.

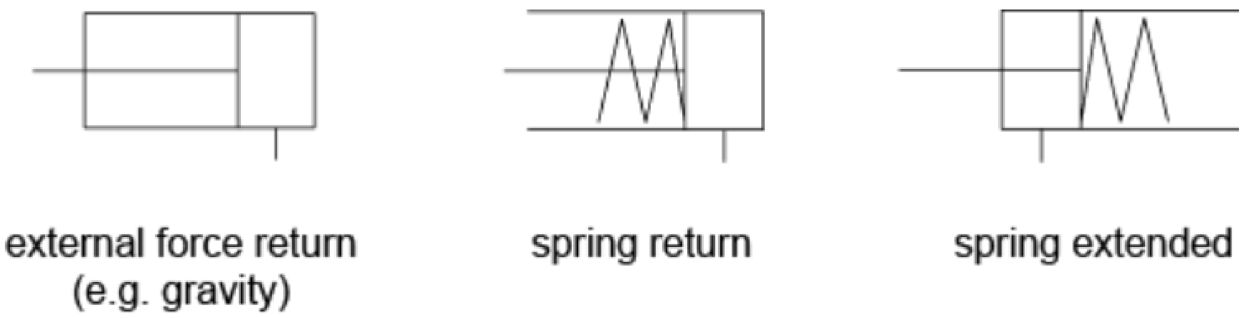


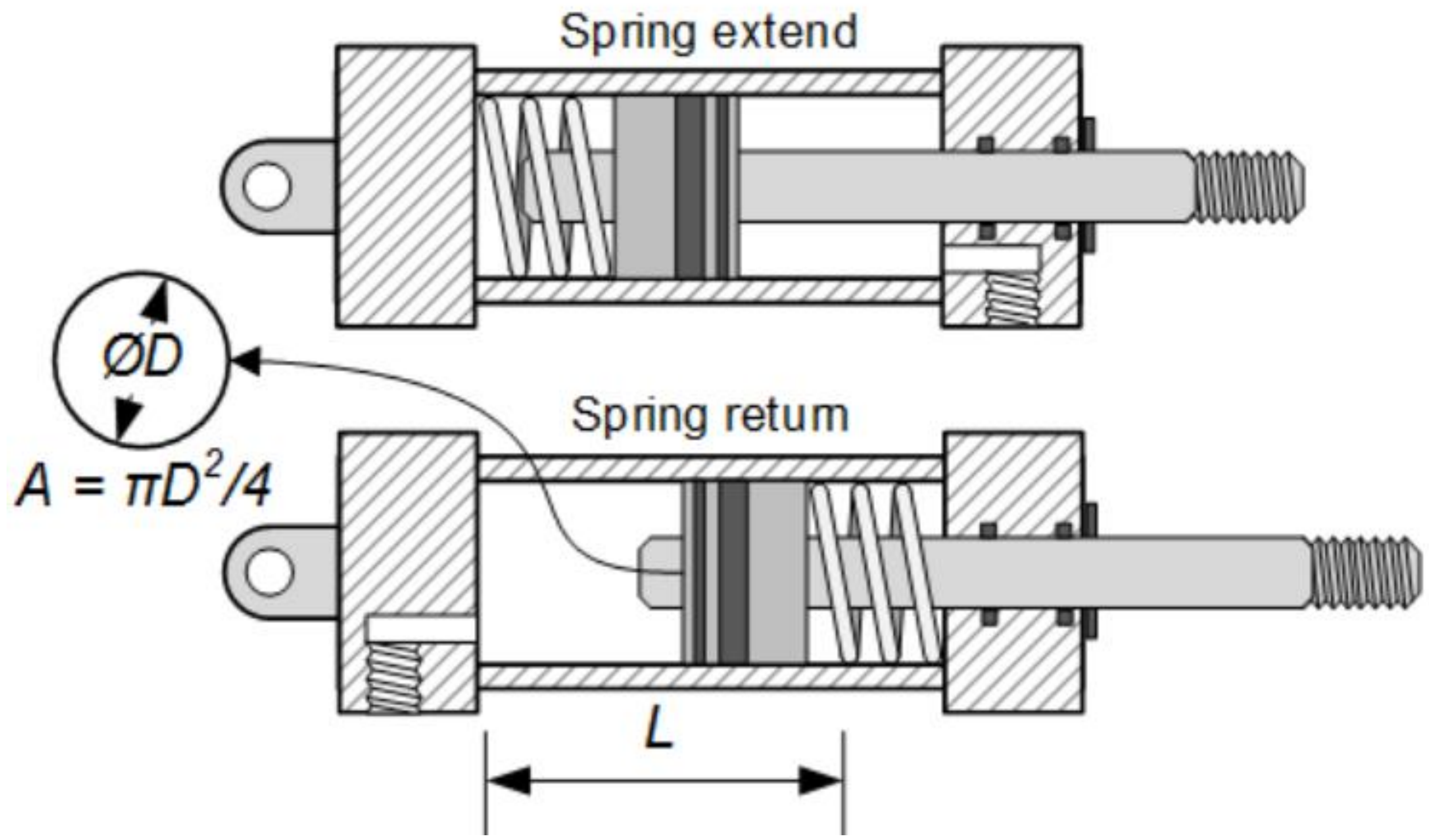
- The impact produced when reaching the end of the run is reduced using a shock absorber.

TYPES OF DOUBLE-ACTING CYLINDERS?

- spring return (common type)
  - In the spring return cylinder, the spring is located between the front end of the cylinder and the piston (around the piston rod)
  - the piston rod extends when compressed air is supplied to the cylinder.
  - As soon as the air supply is cut off, the piston rod retracts by spring force.

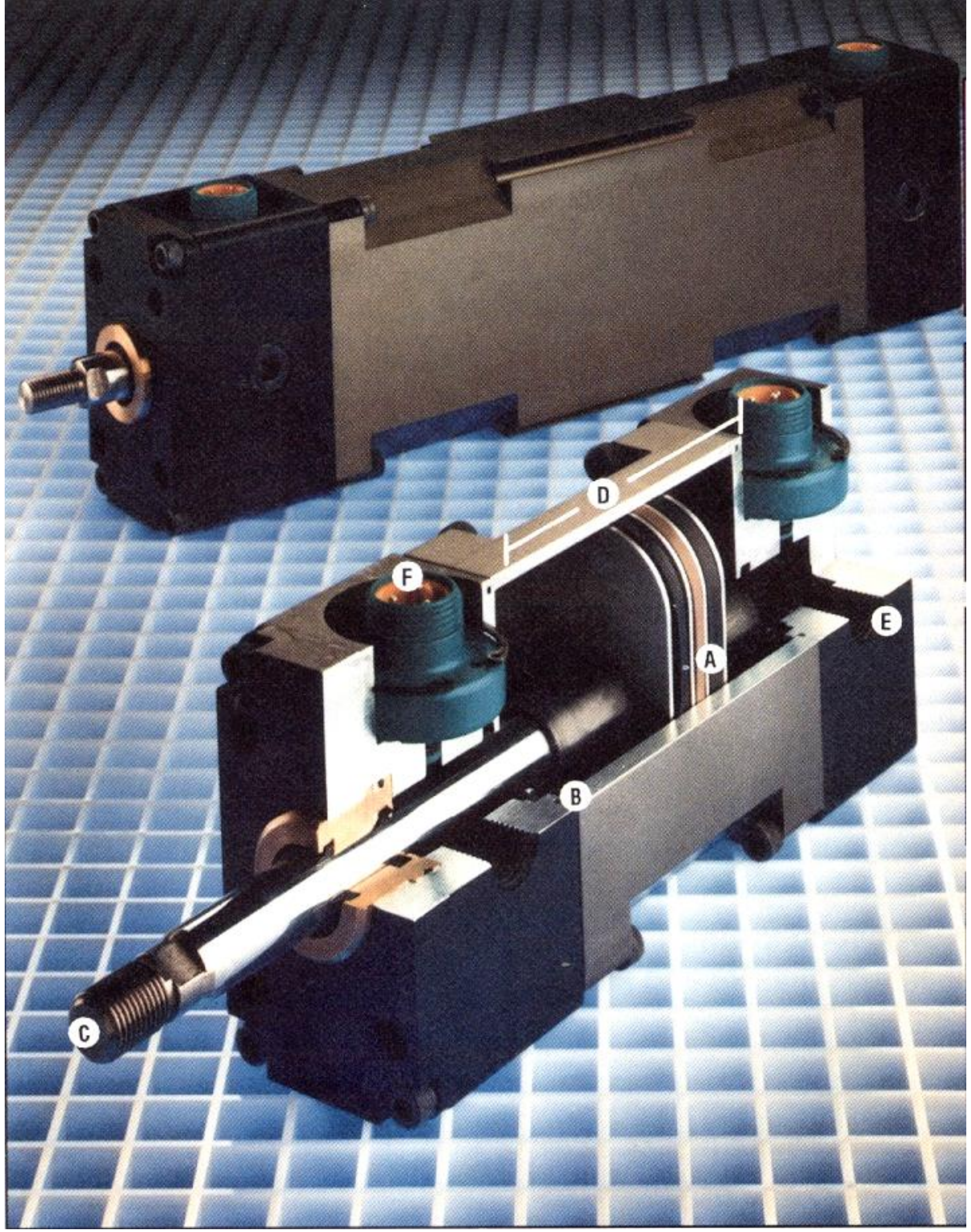
- spring extended
  - the spring is located between the piston and the rear end of the cylinder
  - piston retracts when compressed air is supplied
  - When the air supply is switched off, the spring pushes the rod out



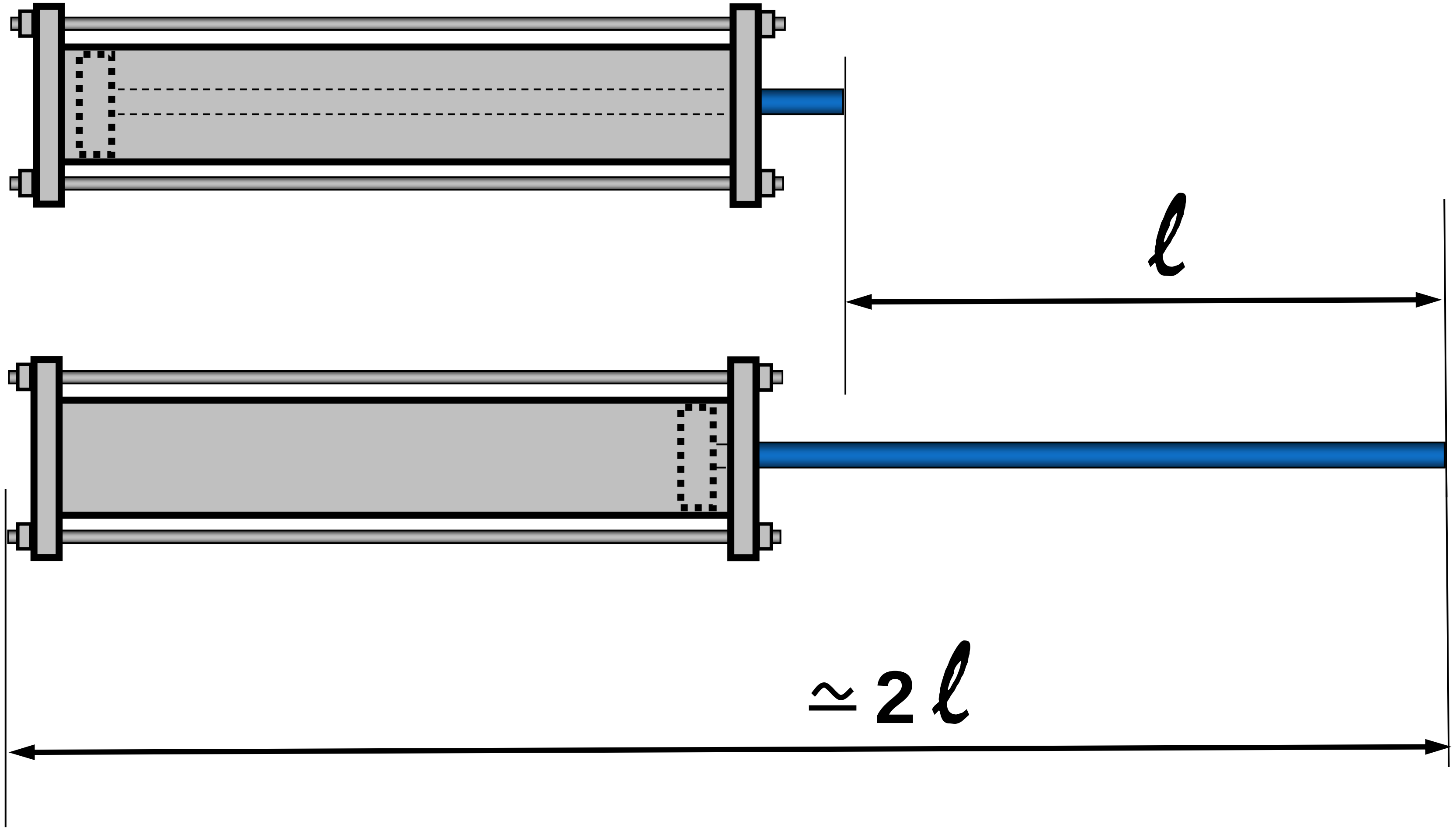

Spring extend
ØD
Spring retum
A = πD²/4
L

Example of commercial pneumatic cylinders

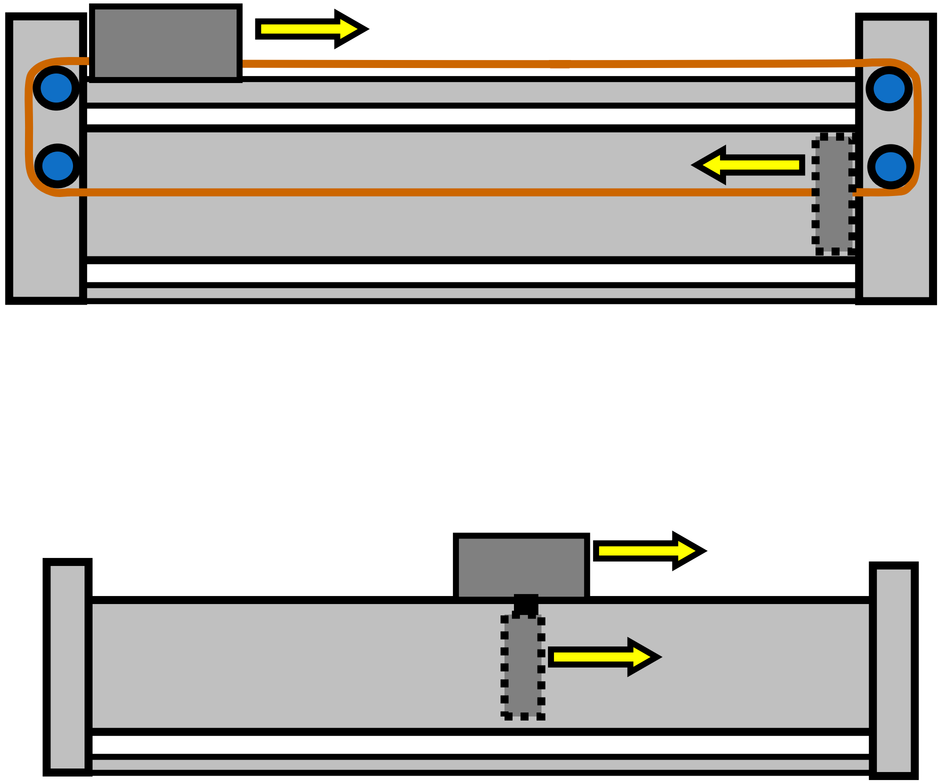
(Lateral guides to prevent axial rotation)



Oval pistons to prevent the rotation of the axis avoiding the need of auxiliary guides



Classical cylinders drawbacks: a displacement of length ℓ requires an additional length ℓ.



$$\Delta\ell \simeq \ell$$

Solutions to reduce the occupied space

PROS OF PNEUMATIC ACTUATORS

Explosion proofing relatively simple

Relatively insensitive to corroding environments if control air is used

Unsophisticated design

Use of control gas possible

Logic interlocking of signals can be realized easily Relatively low cost

High stroking velocities can be realized

“Fail safe outages of the auxiliary energy do not prevent reaching of safe position (spring loaded actuator)”

CONS OF PNEUMATIC ACTUATORS

Distance to the source of energy is limited (dead time problems)

Actuating force of spring loaded units is limited

Auxiliary energy must be generated and made available (cost implications)

Auxiliary energy system requires considerable maintenance

Small systems are normally not economical

Sensitive to changing process pressure

Summary Pneumatic actuators (cylinders)

- Economic
- Reliable
- High operation speed
- Operation at constant force
- Resistant to overloads

- No speed control
- Poor position speed
- Noisy operation

Applications of Pneumatic systems:

- Guided Missiles
- Aircraft systems
- Automation of production machines
- Automatic controllers
- Many more……

HYDRAULIC ACTUATORS

Purpose of the actuator

- to convert hydraulic energy to mechanical energy to preform work

Hydraulic Cylinders are used to create linear motion

Three common types of cylinders

- single acting
- double acting
- telescoping

SINGLE ACTING CYLINDERS

Single acting cylinders are hydraulically actuated

- in one direction only

Two types of forces used to retract single acting cylinders are

- Spring force
- gravity

Two main types of single acting cylinders are

- piston type
- ram type

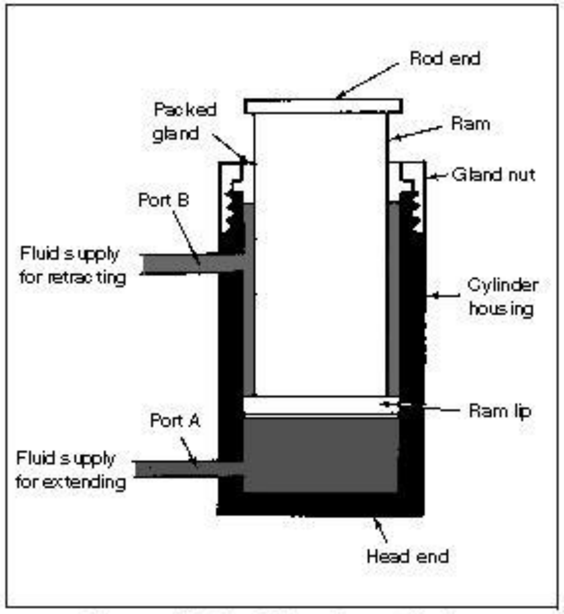


Figure 4-2. Double-acting cylinder

DOUBLE ACTING CYLINDERS

Double acting cylinders are

- hydraulically extended
- hydraulically retracted

Double acting single rod cylinders are referred to as differential cylinders because of

- the difference between extension and retraction speed and the forces they produce due to this

TELESCOPIC CYLINDERS

Why are single acting telescoping cylinders often used on heavy mobile machinery

- to obtain additional stroke length from a relatively compact retracted package

Telescoping single acting cylinders are commonly used on

- Haul truck's dump box where the dump box does not tilt over center.

BELLOWS

An expandable and retractable protective cover that is attached to the rod

used in actuator assemblies to transfer pressure or temperature into a linear motion.

Bellows actuators can be used in valve applications, where pressure is internal or external to the bellows.

With sizes less than half an inch in diameter, bellows actuators can reduce the size of traditional actuators in hydraulic and pneumatic systems.

Often known as pneumatic bellows and hydraulic bellows, edge welded bellows in these applications can save space and improve performance.

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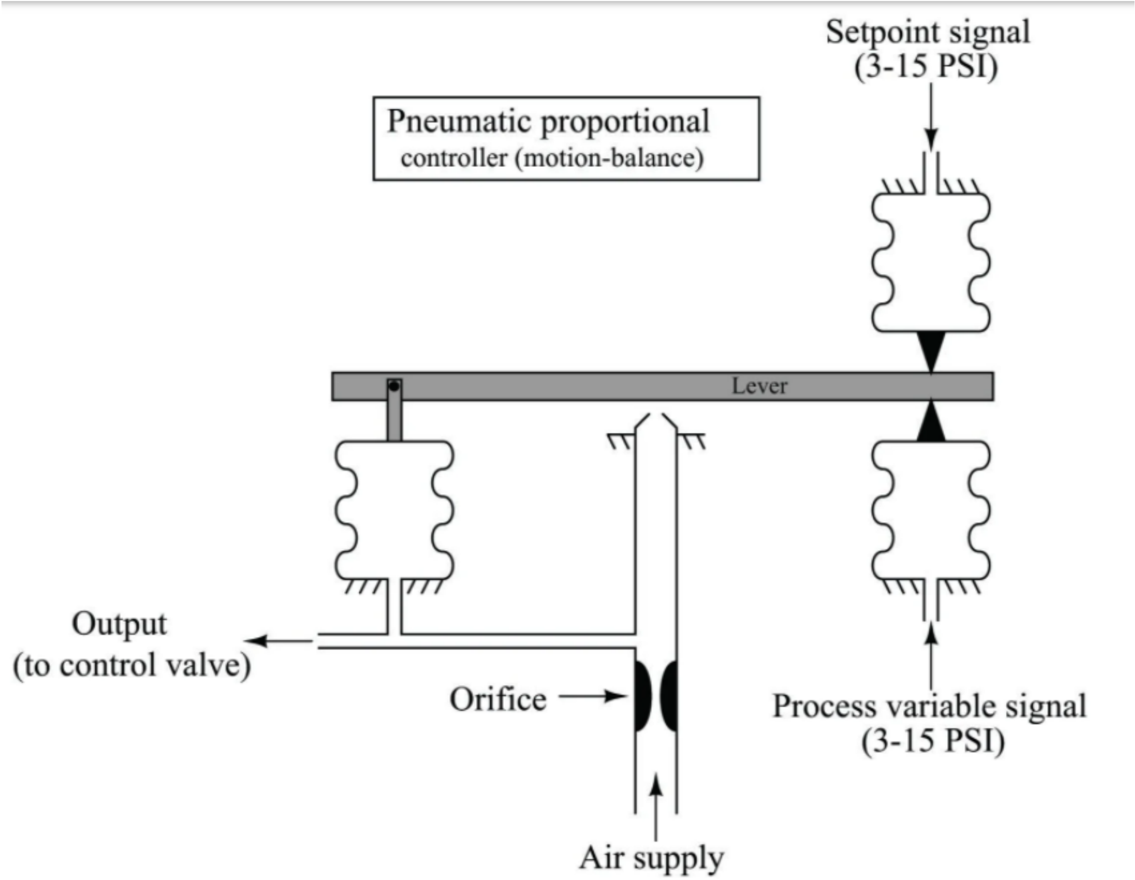

https://control.com/textbook/closed-loop-control/pneumatic-pid-controllers/

PROS OF HYDRAULIC ACTUATORS

High actuating forces

High stroking velocities are possible

High stability

CONS OF HYDRAULIC ACTUATORS

Distance/the source of energy is limited

Tubing is required for transmission of the actuating power, implying additional leakage risks

Costly control

Considerable maintenance requirements

	Hydraulic	Pneumatics	Electrical
Working Fluid	Mineral Oil	Air	Voltage-Current
Working Pressure	500 Bar (maximum	6-7 Bar	Up to 11kV
Available Force	100MN	10kN	100kN
Speed	Low	High	Very High
Conversion Efficiency	Over 70%	Under 20%	Over 80%
Capital Costs	High	Low	Intermediate
Proportional Control	Easy	Difficult	Easy
Hold Load Power-Off/ Stability	Possible	No (air is compressible)	Possible
Precise Positioning	Easy	Difficult	Easy
Environmental Influences	Sensitive in case of temperature fluctuation, risk of fire in case of leakage	Explosion proof, Insensitive to temperature	Risk of explosion in certain areas, insensitive to temperature
Energy storage	Limited with the help of compressed gases	Easy	Difficult, only in small quantities using batteries
Linear Motion	Simple using cylinders	Simple using cylinders	Difficult and expensive – with motion converter
Rotary Motion	Simple	Simple	Simple

CONTROL VALVES

- Used to control the fluid flow of the system
- Control the direction of the fluid by using different ports and positions
- Hydraulic and pneumatic systems require control valves to direct and regulate the flow of fluid from pump (or compressor) to hydraulic cylinders or motors.

TYPES OF FLOW CONTROL VALVES

Pressure control valves

Priority Valves

Orifice check valve

Selector valve

Sequence Valves

Gate valve

Quick disconnect valve

Hydraulic fuses

Flow control valve

PRESSURE CONTROL VALVES

These valves control the pressure of flow medium required by the system

To regulate or reduce oil pressure in certain portions of the circuit

to unload system pressure.

To limit maximum system pressure as a safety measure.

To assist sequential operation of actuators in a circuit by pressure control.

To perform any other pressure related functions by virtue of pressure control.

TYPES

Types

1. Pressure relief valve.
2. Pressure sequencing valve.
3. Pressure reducing or regulating valve.
4. Pressure unloading valve.
5. Pressure brake valve.

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Priority valve

- Allows definite order
- Valve uses hydraulic pressure rather than switches

Orifice check valve

- valve in an aircraft hydraulic system permits fluid to flow freely in one direction, but restricts the rate at which fluid is allowed to flow in the other direction

Relief valves

- used as damage preventing units in pneumatic system

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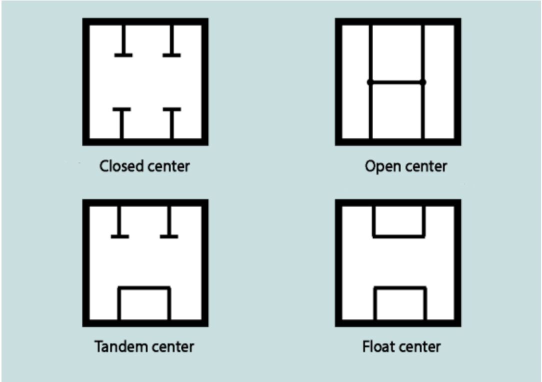
Selector valve

- used to direct flow of fluids in the hydraulic system

Four port, closed center valve

- type of selector valve is one of the most commonly used in hydraulic systems to provide for simultaneous flow of fluid into and out of a connected actuating unit



Gate valve

- Gate valves are not normally used as flow control valves.
- Most of the gate valves are used as stops to shutoff fluid flow (or) to open the line to full flow.
- Gate valves provides a opening with minimum pressure drop.

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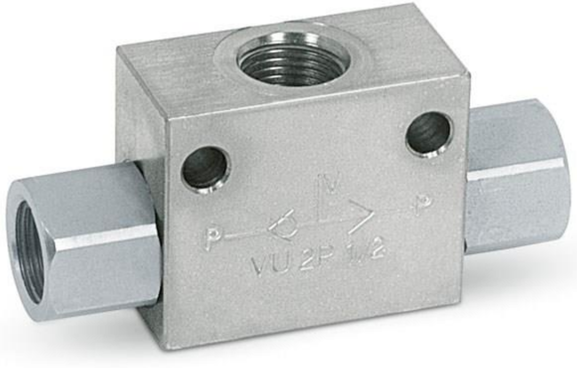

Shuttle valve

- hydraulic component that automatically directs fluid from the normal source or an emergency source to a cylinder

Flap overload valve

- Prevent the flaps from being lowered at airspeed which would impose excessive structural loads

Thermal relief valve

- valve installed in a hydraulic system which has the highest pressure setting

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Quick disconnect valve

- installed in Pressure/suction lines of system. Front or back of pump

Hand pump outport check

- The unit which cause one hydraulic operation to follow another in a definite order

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Needle valve

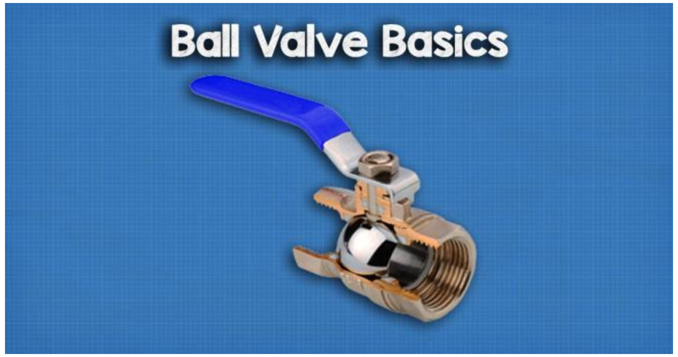
- used in hydraulic systems as both shut-off and metering devices

Ball valves

- may be adjusted from the fully open position to the fully closed position by turning the control handle only 90 degrees (1/4 turn)

Three-way directional control valves

- designed for the actuation of rams and single-acting cylinders



REFERENCE

https://instrumentationtools.com/difference-between-pneumatic-electrical-hydraulic-actuators/

https://nptel.ac.in/content/storage2/courses/112103174/pdf/mod6.pdf

https://bellowstech.com/products/applications/actuators/