IIT Bombay
Makerspace (MS101)
2023 (Autumn)
EE-Lecture-11

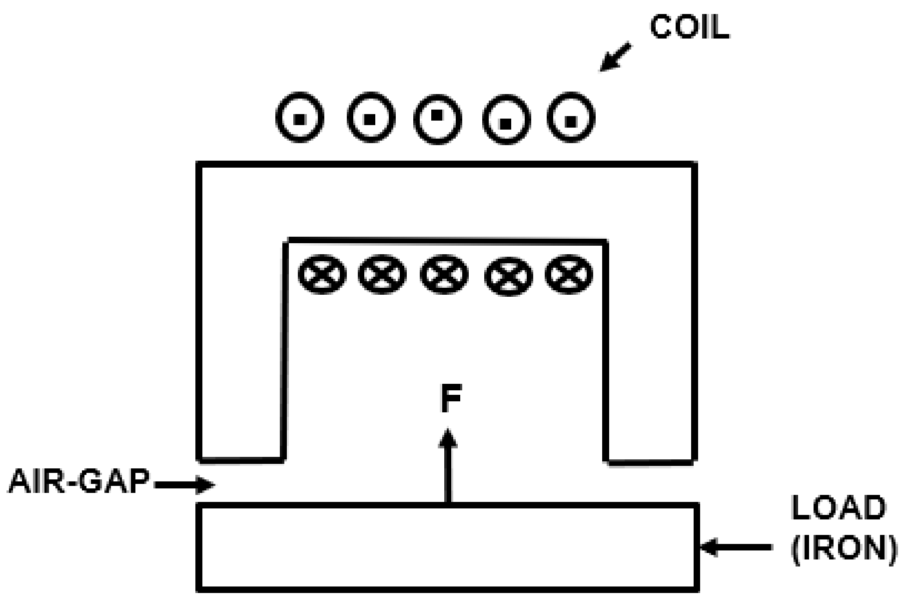
Electro-Mechanical Components

Prof. SV Kulkarni and Prof. Kushal R Tuckley

Electromagnet

- Usually consists of a magnetic core (soft iron or steel) and an exciting coil
- Energy stored in its air gap is used to carry out various functions (lifting material, closing/ opening contacts, etc.)
- The coil when excited results in magnetic field distribution and the corresponding pair of N and S poles
- The direction of the magnetic field can be easily reversed by changing the direction of the coil current
- Reasonably high values of flux density (B) in the air gap can be obtained subject to the saturation flux density of the core and the limit of the excitation current that can be sourced

Application: Lifting of an iron piece



Tractive force across each air-gap: (f) = $\frac{(B)^2 A}{2\mu_0}$

B = flux density in the air gap (assumed as uniform)

A = Cross-sectional area of pole-face

Total force = $F = 2 f$

The design should be such that the total force should be able to balance the weight (= $m g$) of the load

Electromechanical Relays: Types and Functions

Most Common Electromechanical Relays - *Attracted Armature Type*

They consist of

(a) a moving part (armature) capable of making electrical connection with two contacts

(b) an electromagnet (a coil wound on a magnetic core) and

(c) a restraining spring

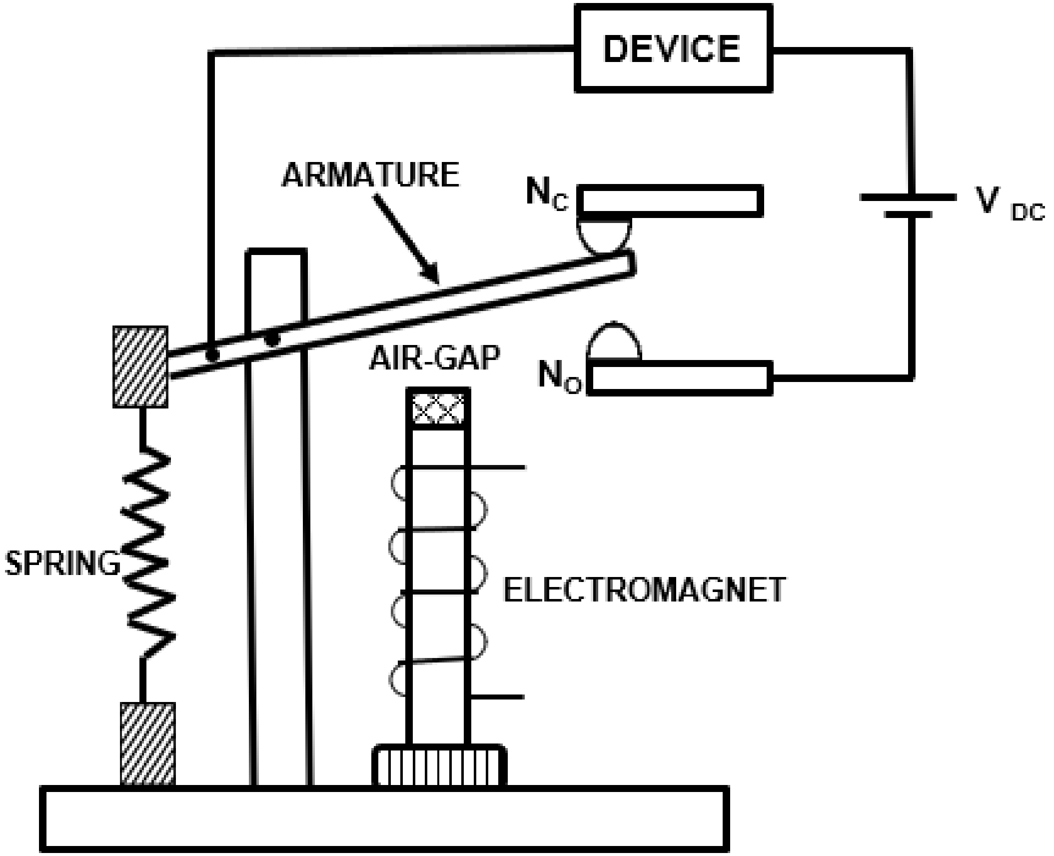
The force on the armature is given by → Force $(F) = KI_{rms}^2 - C$

where, I is the current through the coil, K is a proportionality constant,

C is a constant corresponding to the force offered by the spring

Relay operation depends on the coil ampere-turns, the air-gap between the armature and the core, and the restraining force of the spring

Attracted Armature Type Relay Operation



Operation of an Electromechanical Relay

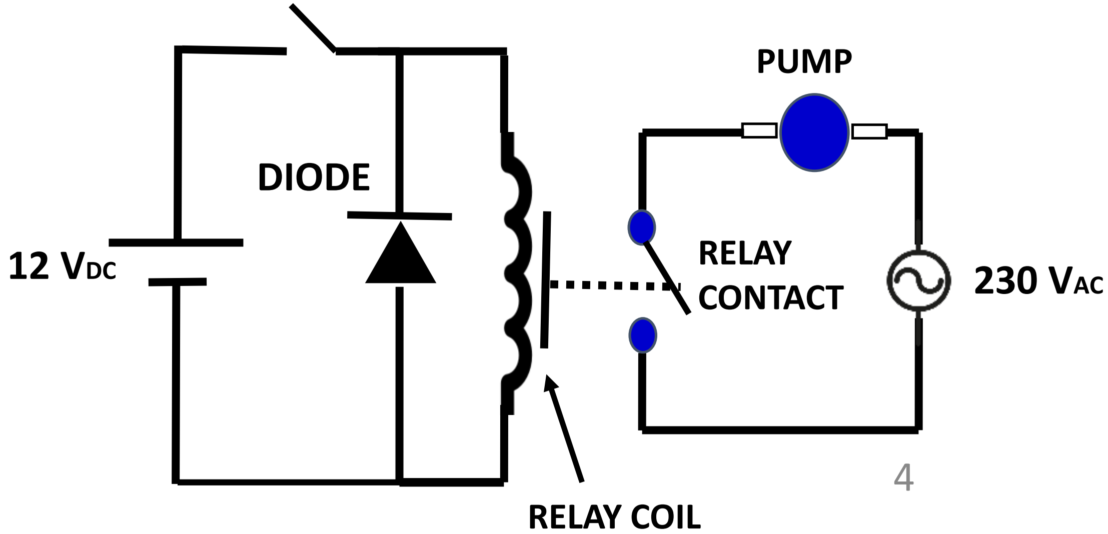
- A coil wound over a ferromagnetic material forms an electromagnet
- When the coil is excited, the armature is attracted towards the NO contact closing the circuit to operate the device
- This relay makes/ breaks the circuit by moving between the two contacts

Armature: Moving part of the magnetic circuit

NC contact: **N**ormally **C**losed in unexcited mode

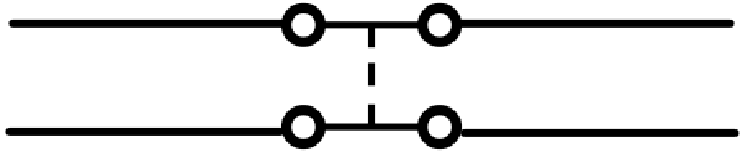
NO Contact: **N**ormally **O**pen in unexcited mode

Water pump ON-OFF control

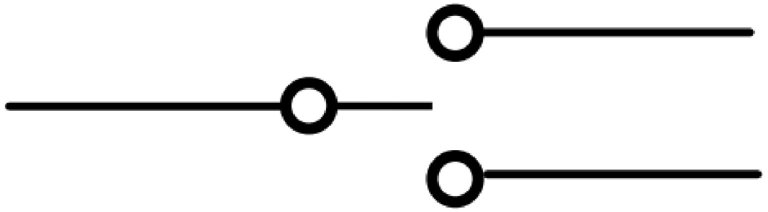


Relay Nomenclature

SPST
Single Pole Single Throw

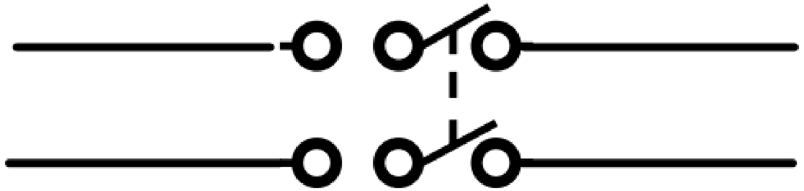


DPST
Double Pole Single Throw



SPDT

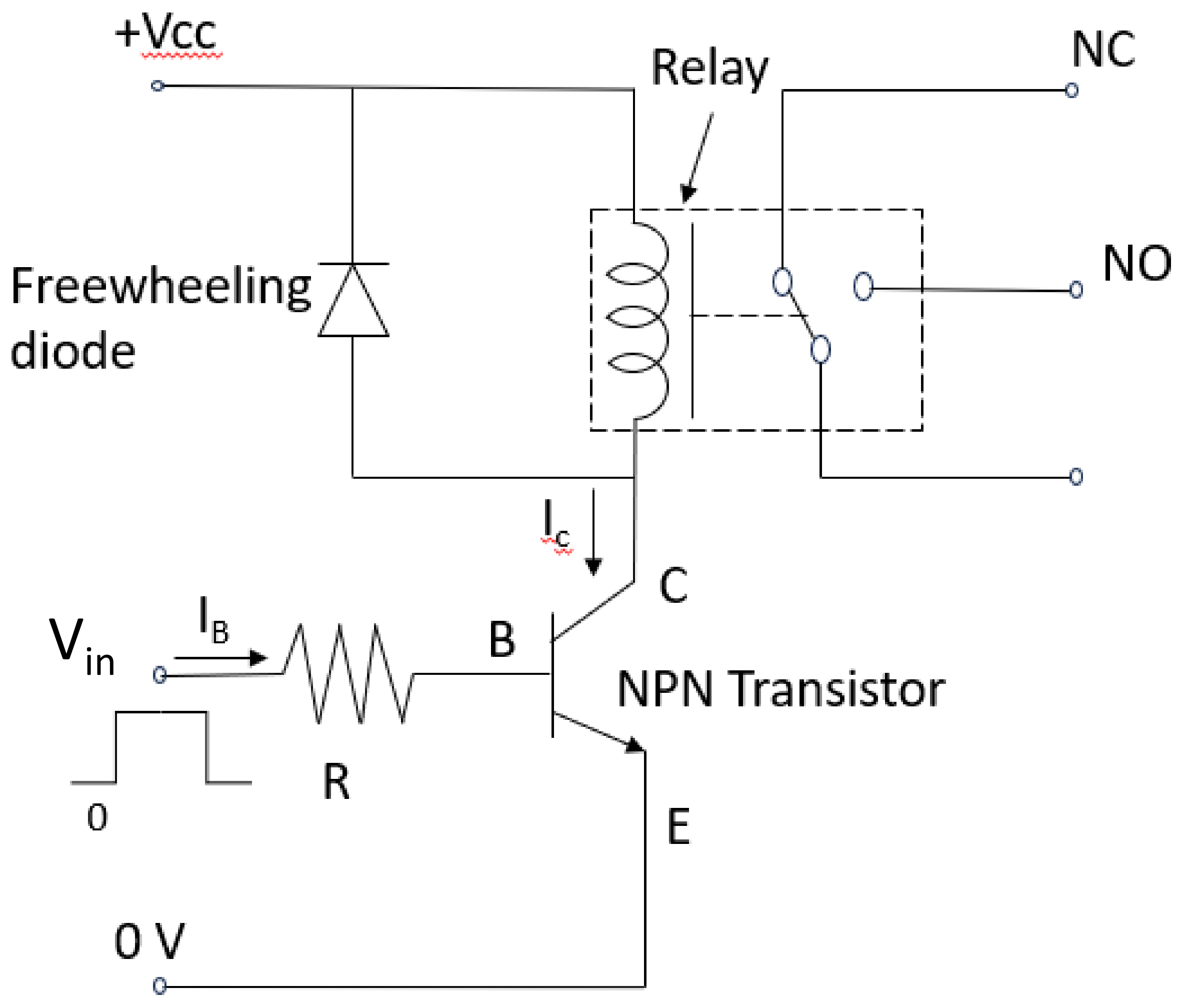
Single Pole Double Throw



DPDT

Double Pole Double Throw

Relay Circuit Using an NPN Transistor



In ON-state:

V_{BESat} (≈ 0.8 V) and V_{CESat} (≈ 0.2V)

Collector current:

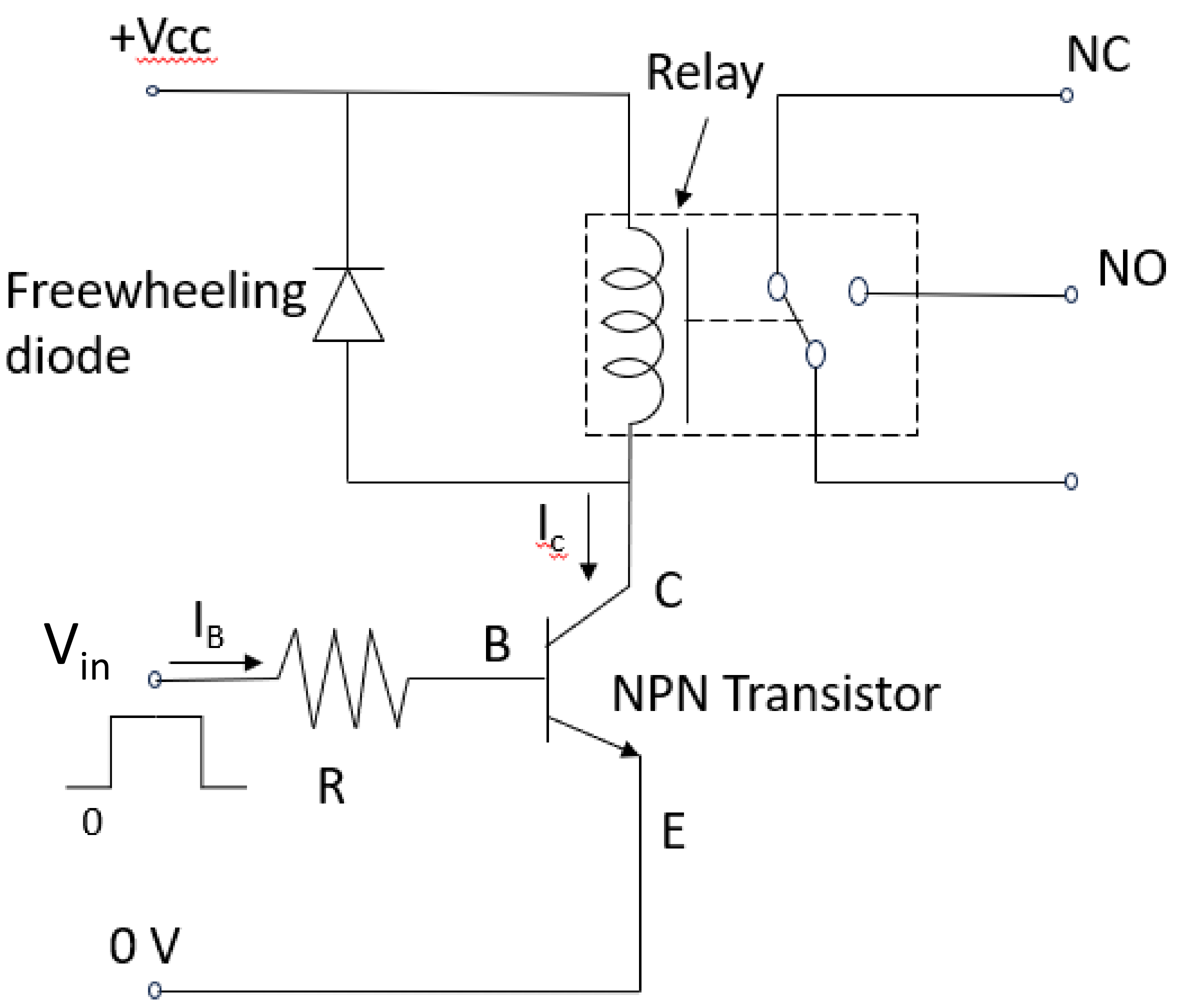
$$I_C = (V_{cc} - V_{CESat}) / R_{coil}$$

Let the current gain ($\beta = I_C / I_B$) in the ON state (saturation mode) corresponding to V_{BESat} be β_{min}

$$\rightarrow I_B = I_C / \beta_{min}$$

$R = (V_{in} - V_{BESat}) / I_B$

- The voltage developed across an inductor is $V = L\, di/dt$
- When the transistor goes to cutoff, a sudden reduction in the coil current gives rise to a large reverse voltage at the collector terminal
- To avoid damage to the transistor, a freewheeling diode is used



Example

$R_{coil} = 71.9\ \Omega$

$V_{CEsat} = 0.2\ V$

$V_{BEsat} = 0.8\ V$

$\beta_{min} = 35$

$V_{cc} = 5.2\ V$

$V_{in} = 0\ \&\ 5\ V$

$$I_C = (V_{cc} - V_{CEsat})/R_{coil} = (5.2 - 0.2) / 71.9$$

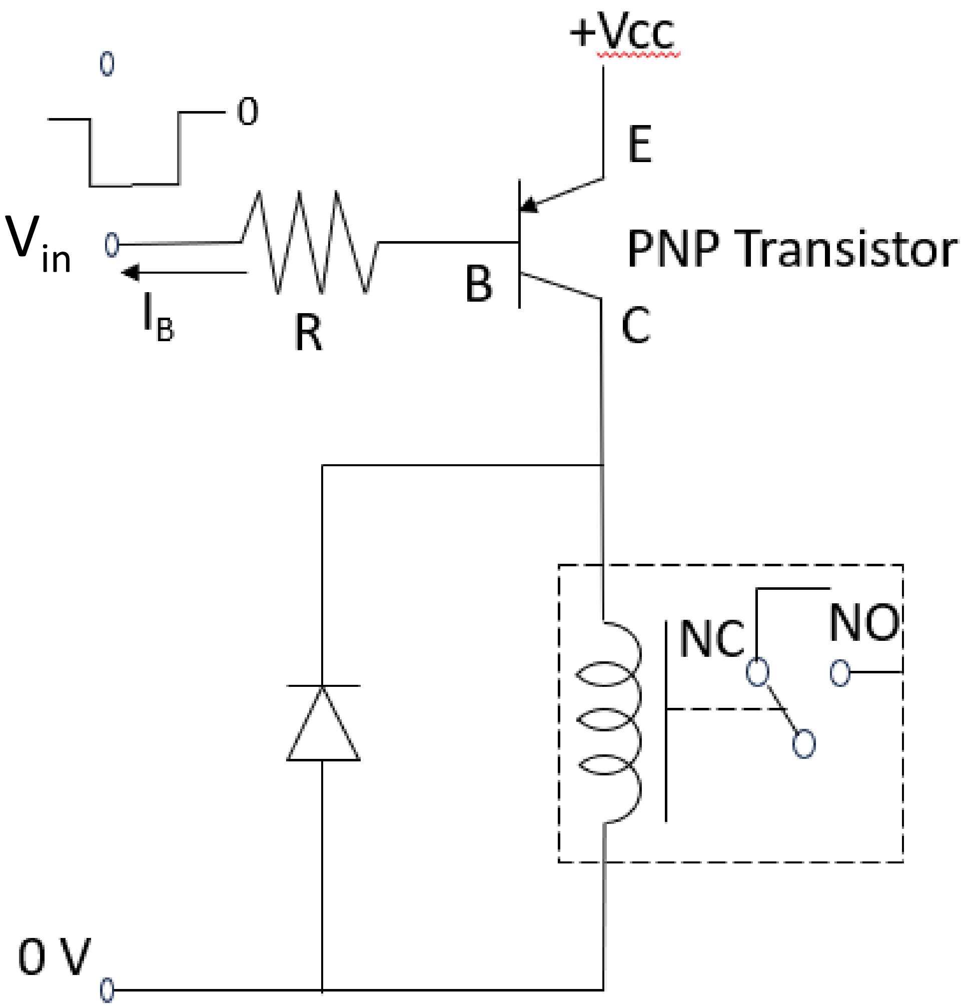
$$= 69.54\ mA$$

$$I_B = I_C/\beta_{min} = 69.54 / 35 = 1.99\ mA$$

$$V_{in} = 5\ V$$

$$R = (V_{in} - V_{BEsat}) / I_B = 2.1\ k\Omega$$

- We can use a PNP transistor also for the relay circuit with the configuration as shown
- Note that the relay is on the collector side
  - PNP transistor: one terminal of the relay is connected to GND
  - NPN transistor: one terminal of the relay is connected to V_{cc}



Solenoids

Solenoids are electromechanical devices that use electrical energy to cause mechanical movement.

Applications: (a) Push or Pull a plunger (linear motion) (b) Realize rotatory motion (over an angle)

(c) Open or close a valve

- Actuators are devices that use either electromagnetic, pneumatic, or hydraulic energy for their operation
- Solenoids are electromagnetic actuators
- Solenoid coils are driven like the relay coils

Electrical current creates a magnetic field

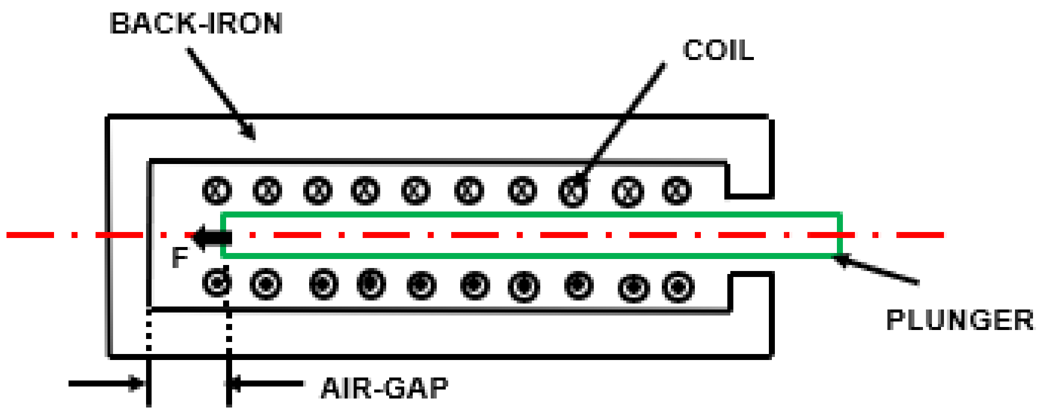
Force: $F = \frac{(B)^2 A}{2\mu_0}$ $\quad B \cong \mu_0 \frac{NI}{l}$

N - number of turns, *I* - current, l - air gap length

A - cross-sectional area of plunger, *B* - air gap flux density

Typical Construction of a Linear Solenoid

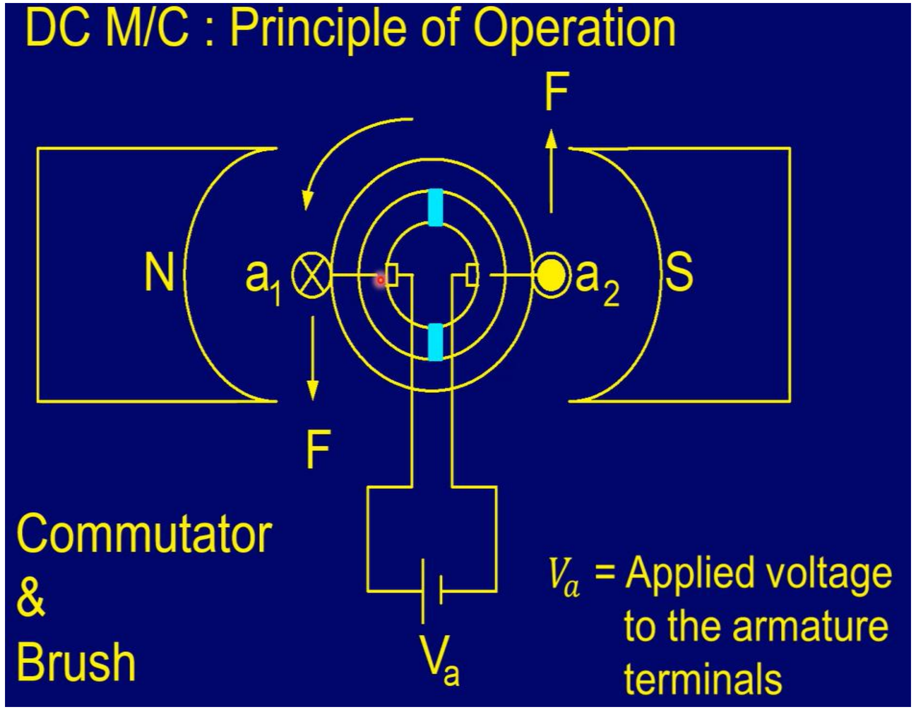
- A movable plunger or armature is placed concentrically inside a coil
- Back-iron provides a low-reluctance magnetic path for flux



Linear Solenoid/ Actuator

DC Motors

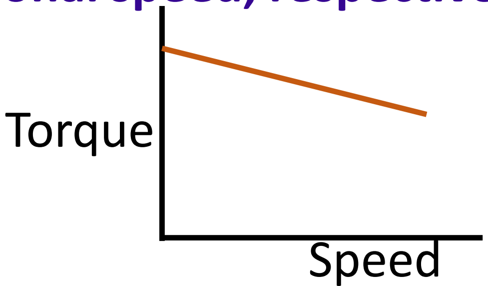
1. Conventional brushed DC motors: stator field is produced by its coils (electromagnets), rotor coils have their two sides (a_1 and a_2 in the figure below) pole-pitch apart under N and S poles



Reference: https://docs.google.com/presentation/d/1s1Fsvb0INAqGS9AAog9YmkMy3jo-zmj6/edit?usp=sharing&ouid=111902402391197382365&rtpof=true&sd=true (To listen to the video, first download the shared PPT file, and then put it into slide show)

- Rotor conductors carrying current and placed in the stator field experience force as per Fleming's Left Hand Rule: index finger – stator field direction, middle finger – current direction, thumb – force direction
- As the rotor moves and the two coil sides exchange their positions, the directions of their currents are reversed by the commutator-brush arrangement to produce unidirectional torque
- A back emf (E_b) is induced in rotor conductors, which opposes the applied voltage (V_a) → $V_a = E_b + I_a R_a$ where I_a and R_a are armature current and armature resistance, respectively
- $E_b = K_e \varphi \omega$ and the torque $T = K_e \varphi I_a$ where K_e, φ, and ω are machine constant, flux, and rotational speed, respectively

$\omega = V_a/(K_e \varphi) - R_a T/(K_e \varphi)^2$



DC Motors

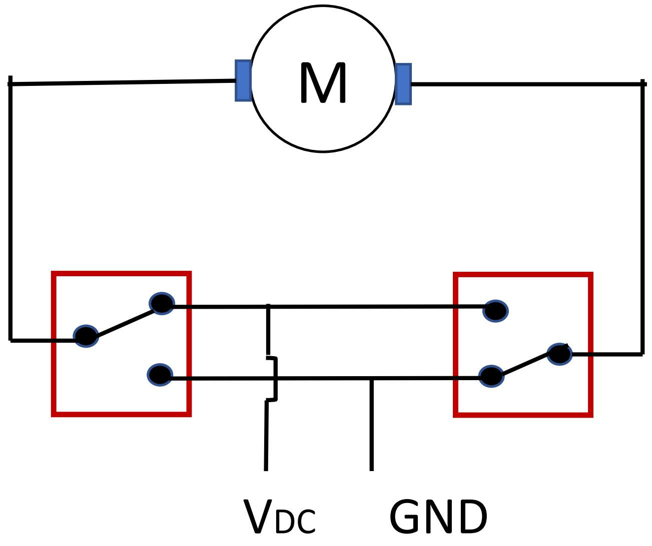
2. **Brushed Permanent Magnet DC (PMDC) motors: the stator field is produced by a pair of permanent magnets and the rotor has a set of electromagnets as in battery-operated (BO) motors**

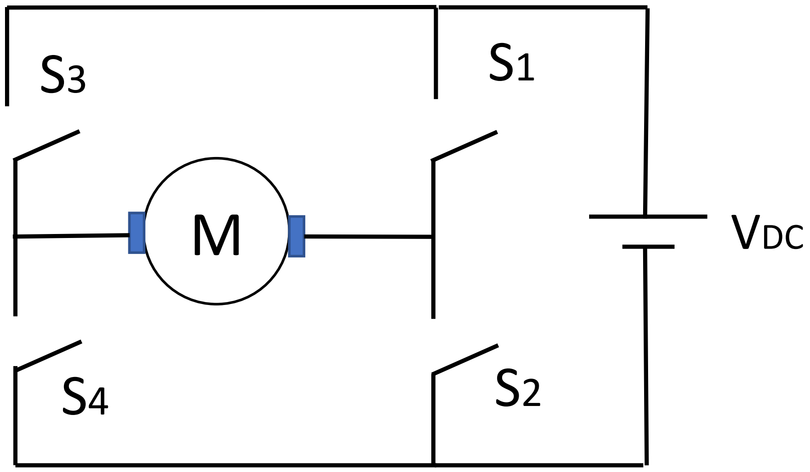
   - **The direction of currents flowing in the rotor coils forming electromagnets are changed appropriately through the commutator-brush arrangement to produce unidirectional torque in accordance with the principle that like poles of the stator and the rotor repel and their opposite poles attract each other**
   - **When the current is being reversed in the rotor coils, due to their inductance the currents may get reversed before they become zero; this results in the interruption of non-zero currents and sparking between the commutator segment and the brush (stored energy in the inductor of the motor-system appears as a voltage spike across the stray capacitance between the two parts)**
   - **To mitigate the effect of sparking (voltage spikes) on the connected electronic components in the circuit, a suitable capacitor is connected across the BO motor terminals (as done in experiment 4)**
   - **The speed of a BO motor can be varied by changing the applied DC voltage (V_a) using the PWM technique and the direction of the rotation can be controlled using an H-bridge**

Reference Material:
Battery Operated (BO) Motors: Refer to the writeup on BO motors shared earlier

Reversing Direction of Rotation by Current Reversal

Direction Reversal of a DC (BO) Motor Using 2 SPDT Switches





S1	S2	S3	S4	Action
0	0	0	0	Motor Coasts
0	0	1	1	Short Circuit
0	1	0	1	Breaking
0	**1**	**1**	**0**	**CW Movement**
1	**0**	**0**	**1**	**ACW Movement**
1	0	1	0	Breaking
1	1	0	0	Short Circuit
1	1	1	1	Short Circuit

The motor speed and direction can be controlled electronically by using transistor switches and freewheeling diodes. These circuits are available as motor driver cards (for example L298).

DC Motors

3. **Brushless DC (BLDC) motors: the rotor is of inner or outer type with permanent magnets and the stator has electromagnets with currents in coils commutated electronically**

- Disadvantages of brushed motors: high maintenance and short lifespan because of wear and tear of brushes, and low efficiency on account of friction between brushes and commutator segments (energy loss and heat)
- Brushless motors: higher efficiency, lower maintenance, compactness, higher power-to-size ratio, and lower noise
- The stator houses a star or delta-connected three-phase coils (acting as electromagnets)
- Electronic speed controllers commutate currents in the stator coils producing unidirectional torque: the currents in the stator coils are switched appropriately as the rotor rotates
- Typically, in most of the BLDC motor applications requiring precise control of torque, the rotor position is sensed by a Hall effect sensor, and accordingly the electronic switches of the converter are controlled to reverse currents at appropriate time instants

Reference Material:
Brushless DC Motors: Refer to the writeup being shared along with this presentation

4. Servo DC motors: used in applications requiring precise control of speed, torque or position

These motors, also called as rotary actuators, are used in applications requiring precise mechanical movements with the control variable as angular position or angular velocity

Components

1. DC motor
2. Position sensor (potentiometer connected to motor shaft)
3. Gearbox (for obtaining high torque and low speed)
4. Feedback system (closed loop system)
5. Control electronics

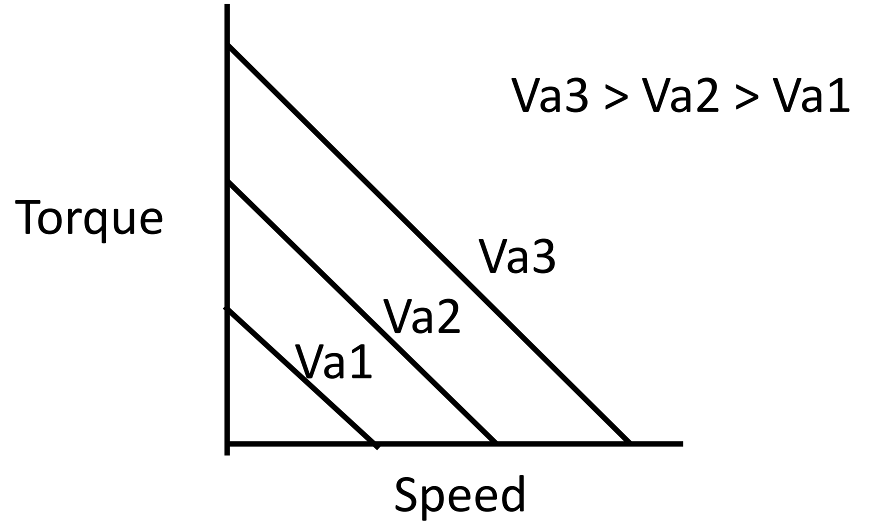
Applications

Robotics, industrial manufacturing, machine tools, packaging, printing, automatic doors, steering systems of antennas, etc.

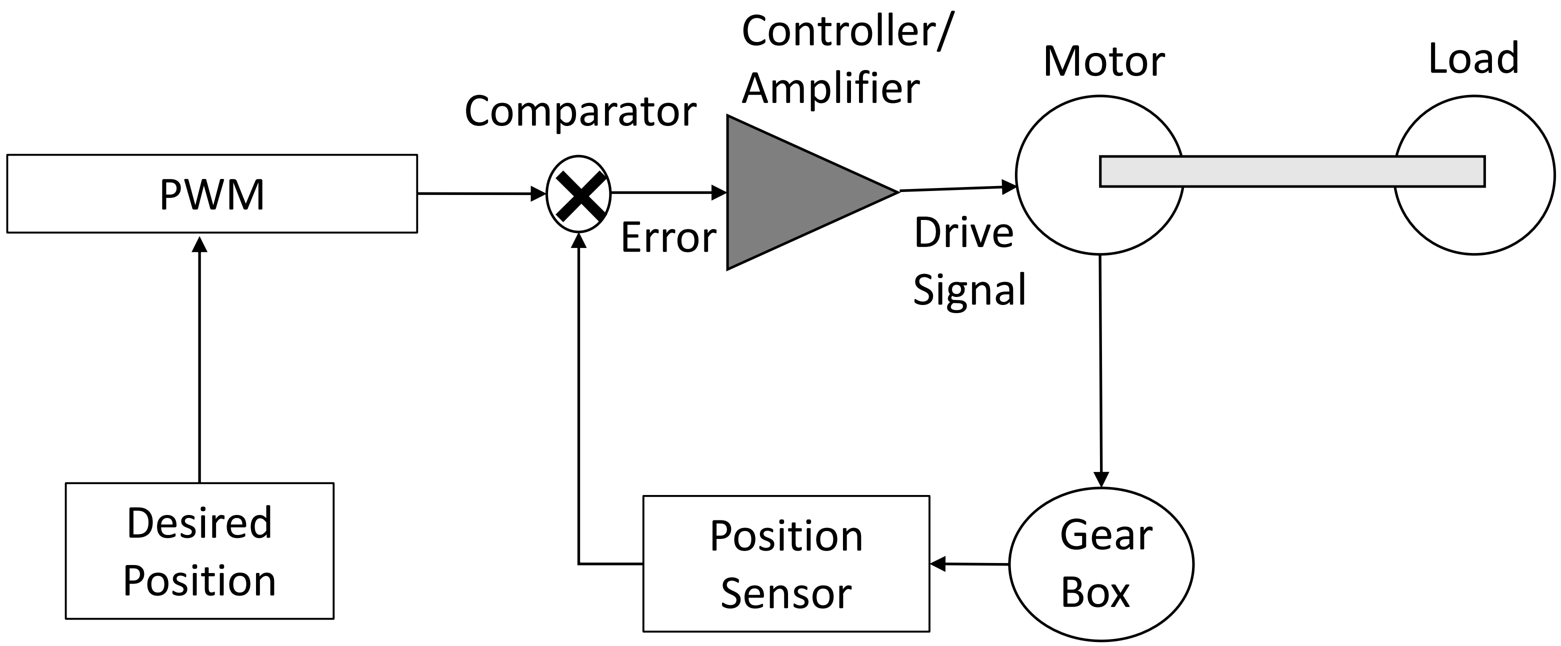
A typical DC servomotor has 3-pins:
(i) Supply (ii) Ground, and (iii) Control (PWM)

DC Servomotor Characteristics and Operation

- DC motor: PMDC (brushed) or BLDC or with a separate field-coil excitation
- High torques at low speeds (achieved through a gear box)
- Low inertia and fast response (motor construction with small diameter and long length)
- Not designed for continuous rotation (typically designed to operate over 0 to 180 degrees in less than one second)
- PWM control applied to the armature (applied voltage, Va, is changed with suitable duty cycle)
- High-resistance armature winding: a large negative slope in torque-speed characteristics provides viscous damping



Control of a Servomotor

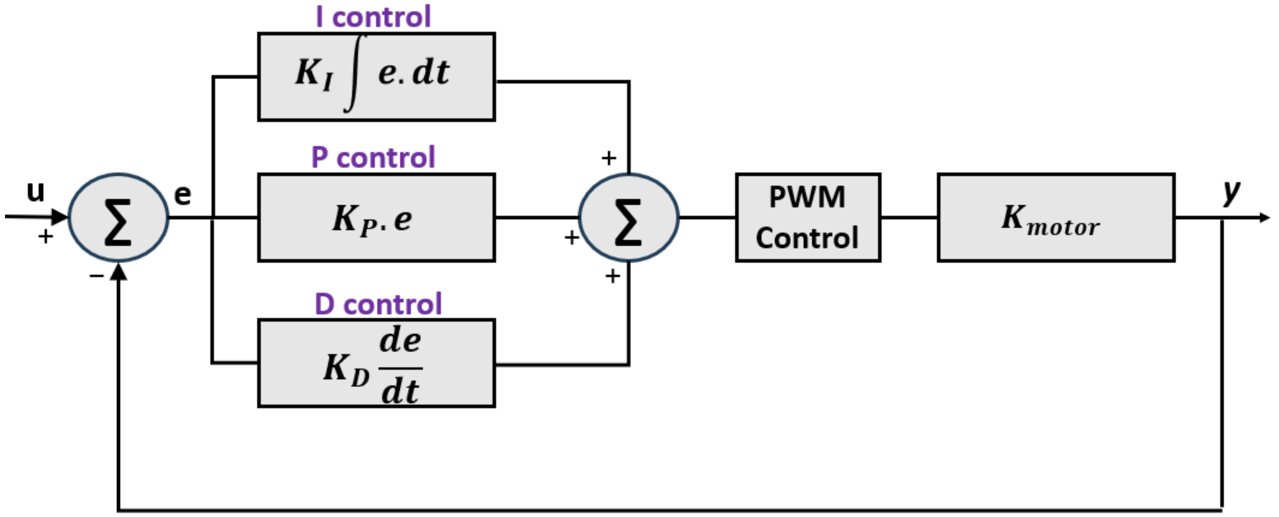


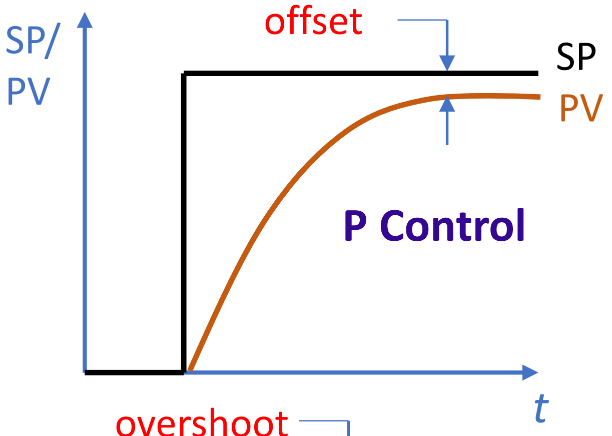
- **Operated with a close-loop feed back with a position sensor (typically a potentiometer)**
- **The error signal depends on the difference between the actual and desired positions**
- **The drive signal to the motor should be such that the error is eventually reduced to zero, for which either proportional (P) control, proportional and integral (PI) control, or proportional, integral, and derivative (PID) control technique is used**

Reference: https://www.elprocus.com/dc-servo-motor/

Motor Control

- P Control: $e = u - y$, controller output: $K_p \cdot e$ → a simple control approach, but it leads to a non-zero error (offset: $\frac{u}{1+K_{motor} \cdot K_p}$) in steady state
- PI Control: accumulated (integrated) error over some time is used to eliminate the offset (associated with P control), however this control strategy may result in an overshoot if the error accumulated in the initial period is high
- PID Control: derivative control block checks the rate of change of the error and dampens the overall gain by adding a term proportional to the negative of the rate, which helps to eliminate an overshot (if present)
- Depending upon the response of the system (overshoots/ undershoots, fast/ slow response, etc.), the three controller gains need to be appropriately adjusted in a coordinated way to achieve desired control characteristics





u = Set Point (SP)
y = Process Variable (PV) (speed or position)
e = error = SP – PV
K_P, K_I, K_D = *controller* gains