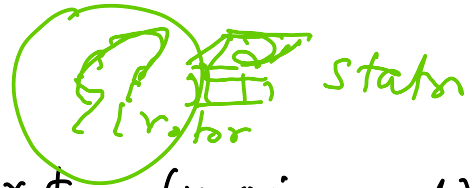
② Brushless DC motor

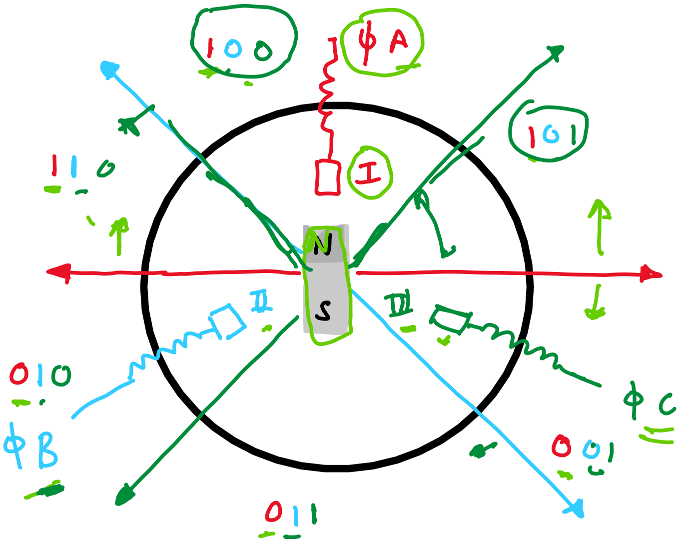


- In a brushless motor the rotor (moving part) has a permanent magnet and the stator (stationary part) has coils.
- NOTE: The brushed motor construction is reversed: permanent magnet is the rotor and coils is the stator
- In a brushless motor the commutation (maintaining continuity in current and hence motor spin direction) is done by electrical means. This makes control harder compared to brushed DC motor

- Brushless DC motors offer the following advantages over brushed DC motors

1) Brushless motors don't have brushes. Brushes introduce acoustic and electrical noise and wear out.
2) Rotor (permanent magnet) does not have windings. This makes the rotor light. A lighter rotor can spin faster for the same voltage/current compared to a brushed motor
3) No brush friction
4) No brushes means less resistance and less dissipation
5) Coils (resistive part) are on the outside, they can thermally dissipate the heat (i.e. I^2R)

The stator is available as 1-phase, 2-phase, 3-phas configurations. where phase refers to the number of independent windings on the stator. The 3-phase winding is shown below. The phases are wired in the Y configuration.

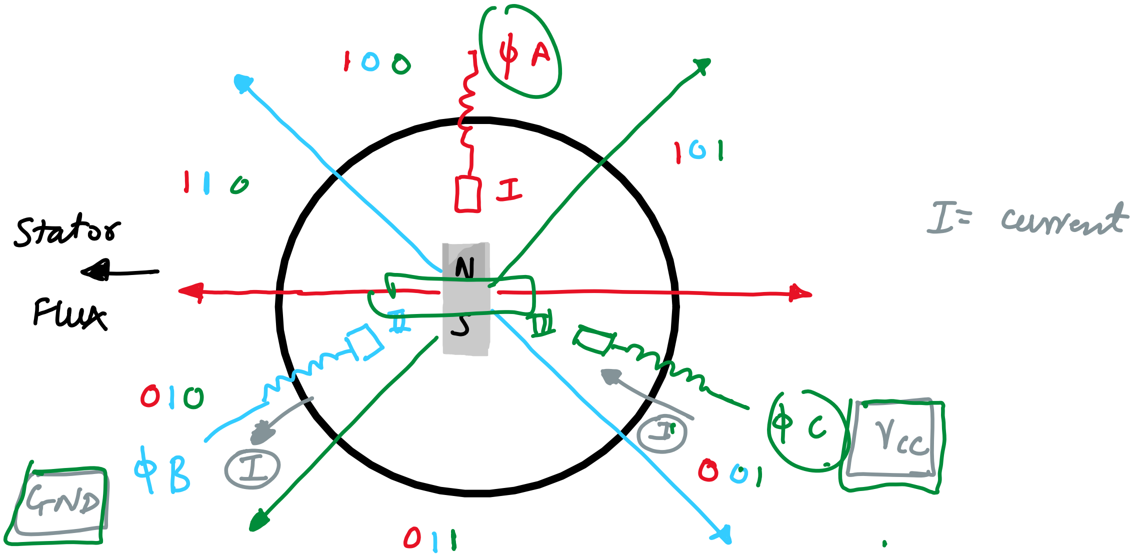


- A, B, C are phases
- I, II, III are hall-effect sensors
- The motor has 8 wires
  - 3 for the 3 phase (A, B, C)
  - 5 for hall-effect sensor
    - Vout for each sensor (I, II, III)
    - V_{cc} & GND

100 Is 1 if N pole is within 180° of the correspond stator ϕA, ϕB, ϕC.

see this

- The Hall-effect sensor will output 1 when the north pole is within 180° & 0 otherwise
- This splits the rotor in 6 zones, each with a different code as shown to the left



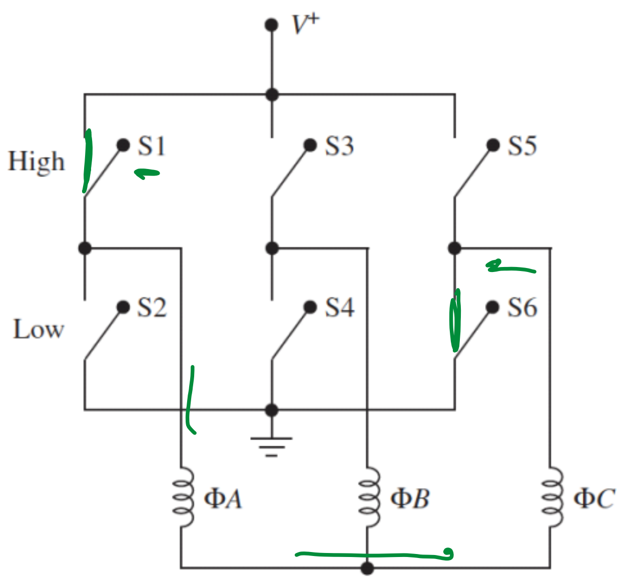
→ Here is how commutation is done to rotated the rotor

We assume N pole is UP as shown above and we are interested in rotating to rotor in CCW direction.

- Connect ϕC to V_{cc} and ϕB to GND
- This cause current I to flow from ϕC to ϕB
- The current causes a stator flux pointing to the left as shown.
- This flux causes the rotor (and hence motor) to turn CCW,
- However, once the rotor becomes horizontal, one needs to swim ϕA to V_{cc} and ϕC to GND

The table below shows how to commute for CW and CCW motion

Sensor Output			CW Rotation			CCW Rotation		
C	B	A	ΦA	ΦB	ΦC	ΦA	ΦB	ΦC
1	0	0	NC	Hi	Low	NC	Low	Hi
1	0	1	Low	Hi	NC	Hi	Low	NC
0	0	1	Low	NC	Hi	Hi	NC	Low
0	1	1	NC	Low	Hi	NC	Hi	Low
0	1	0	Hi	Low	NC	Low	Hi	NC
1	1	0	Hi	NC	Low	Low	NC	Hi



- Commutation / Speed control is achieved using 3-phase bridge drives that consist of 3 half bridges
  - Example: closing S_1 and S_4 will connect ϕ A to V^+ and ϕ B to GND; C will float
  - To reverse the current flow S_2 and S_3 are closed
  - Brushless motors are used to control fans in computers.

③ Servo motors

These are DC motors fitted with a position sensor (e.g. encoder). They have 3 inputs: V_{cc}, GND, V_{input}. V_{input} can be set to the desired position

Stepper motor

This is a DC motor that can be driven a few degrees per step depending on their construction and control circuitry

The features of stepper motors are as follows

1. They can achieve position control without feedback (no sensors)
2. No wires to the rotor hence no need for brushes/commutation
3. They can generate large torques at low speeds without the need for gears.

There are 3 types of stepper motors

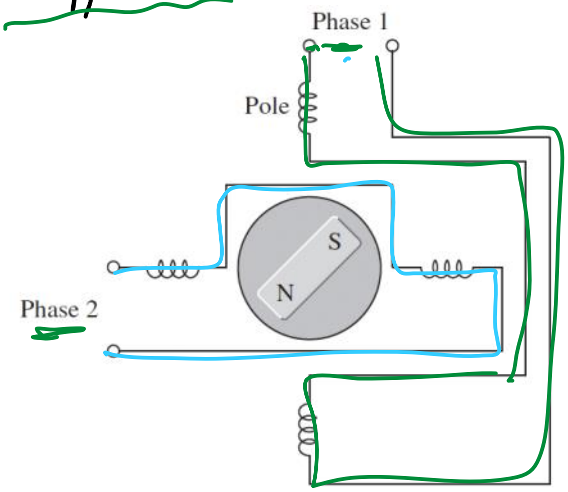
1. Permanent magnet stepper motor (PM): The rotor is a permanent magnet and has no teeth
2. Variable Reluctance Motor (VR): The rotor is a non-magnetized soft iron core and has teeth
3. Hybrid motor: This combines PM and VR motor. The rotor has a permanent magnet and teeth.

VR motor has a fast dynamic response

PM motor can exert a small holding torque when the stator is not energized due to the use of magnetized rotor. PM motors are used in non-industrial applications such as computer printers

Hybrid motors: used in industrial applications.

Stepper motors explained using two phase permanent magnet stepper motor.

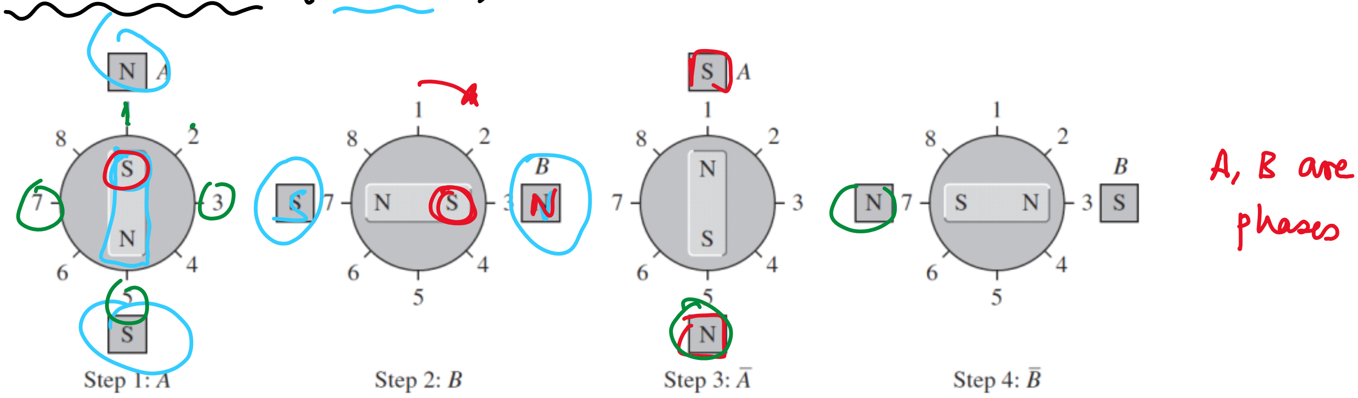


- Phase: Coil winding
- 2 phase: 2 separate coil windings
- 4 poles poles in the stator: stator 2 poles per phase
- 2 poles in the rotor: 1 magnet with N-S poles. moving

Drive methods

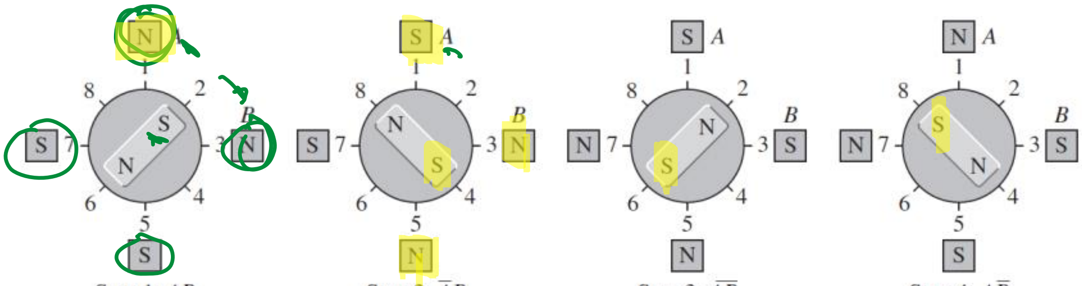
① Wave drive ② Full stepping ③ Half Stepping ④ Micro stepping

① Wave drive (2 phase, 90°)



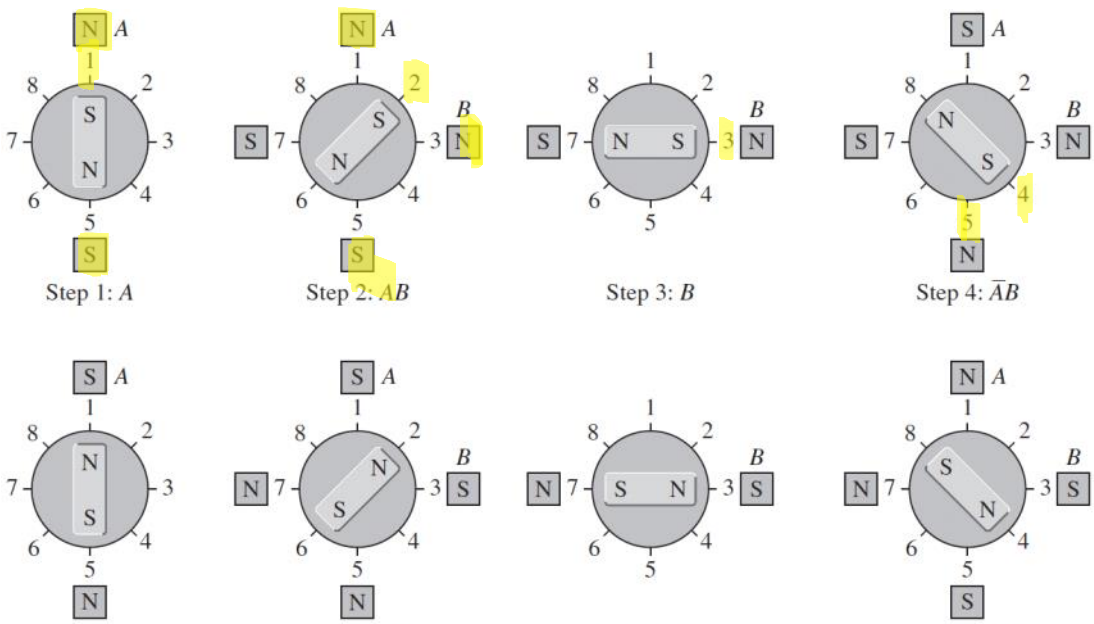
- CW rotation: A, B, $\bar{A}$, $\bar{B}$ are turned ON in that order
- CCW rotation: $\bar{B}$, $\bar{A}$, B, A are turned ON in that order
- Rotor goes in 90° steps as shown: 1-3-5-7 position. By increasing the number of phases, finer resolution can be achieved.
- Only 1 out of 2 phases are ON. Thus net torque is only 50%. of maximum torque. For N phases, the torque is $\frac{100}{N}$ %.

Full stepping actuation (2 phase, 90°)



- Both phases are ON, gives 90° rotation in positions 2-4-6-8
- Full Torque as both phases are ON

Half Stepping Actuation (2 phase, 45°)

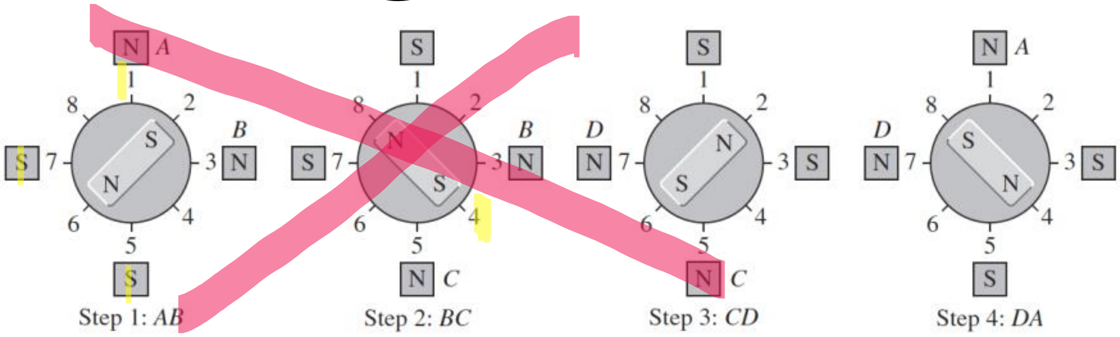


- alternates between active one phase and active 2 phase
- gives 45° rotation; 1 through 8.

All activations discussed so far require bipolar excitation. This complicate the control circuitry.

This complicate the control circuitry.

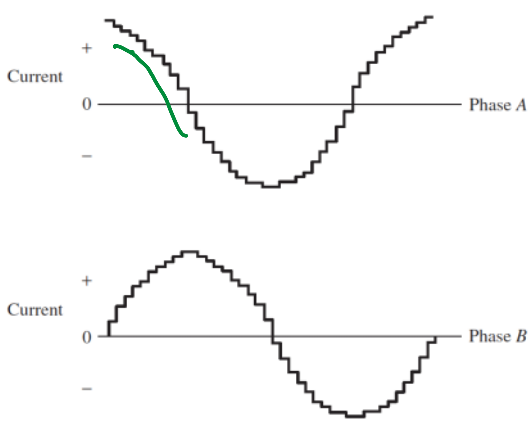
Half wave : 4 phase, 45°



- This achieves 45° rotation using 4 phases.
- A, C have 2 phases & B, D have 2 phases

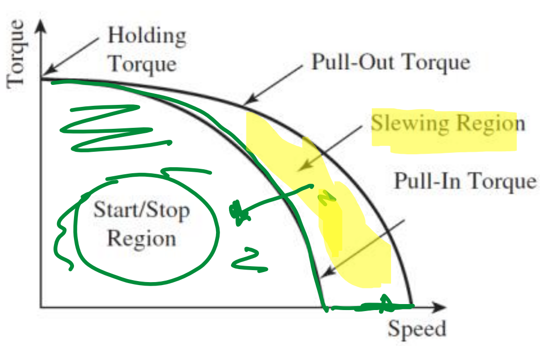
  Each has a fixed polarity which can be switched.

Micro-stepping drive



- Instead of phases going ON/OFF like previous methods, if one lets the voltage to vary from 0 to Vmax one can get a finer resolution

Torque / Speed curve



There are 2 regions

① Start / Stop region : The motor can start, stop and reverse instantaneously

② Slewing region: The motor cannot stop instantaneously. It needs to

stop instantaneously. It needs to pass through start/stop region

Selecting a motor

1. **Motor acceleration:** $\alpha = \dfrac{T - T_f}{J}$; T, T_f : motor / frictional torque
   J : inertia
   α : acceleration

2. **Max speed:** $\omega_{max} = \dfrac{V_{max}}{k_e}$; k_e : electrical motor constant

3. **Power needed:**

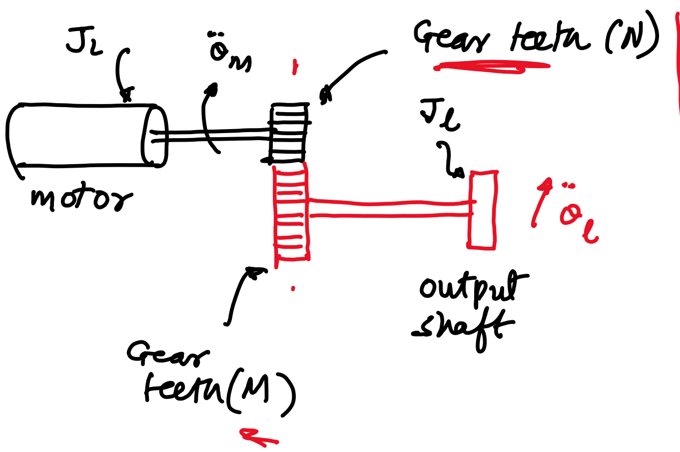
   $P = T\omega$ & $P_{max} = \dfrac{T_s\,\omega_{max}}{2}$

4. **Power source:**

   DC or AC

5. **Type of control:**
   - Position: Servo or Stepper motor
   - Speed: DC motor

6. **For torque amplification** use appropriate gearing



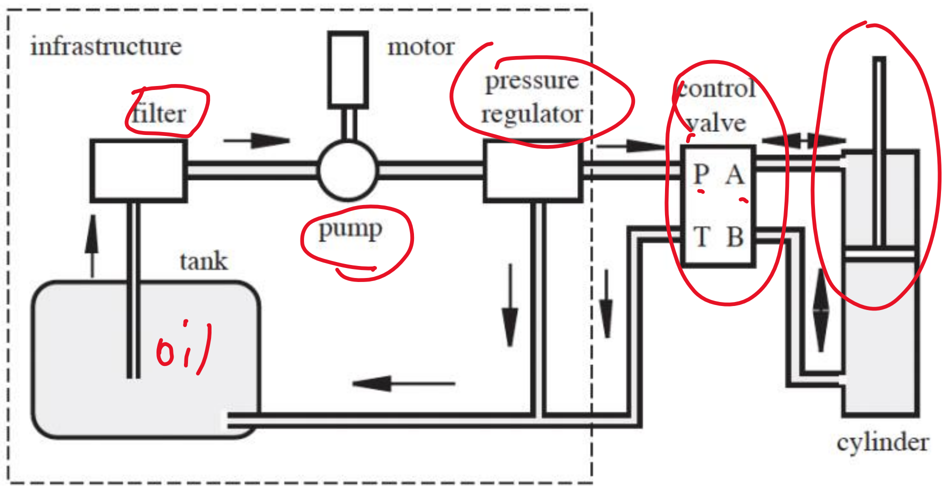
$$T_{net} = T - T_f = \frac{M}{N} J_\ell \ddot{\theta}_\ell + J_m \ddot{\theta}_m$$

But $\ddot{\theta}_\ell = \left(\dfrac{M}{N}\right) \ddot{\theta}_m$

$$T - T_f = \left(\frac{M^2}{N^2} J_\ell + J_m\right) \ddot{\theta}_m$$

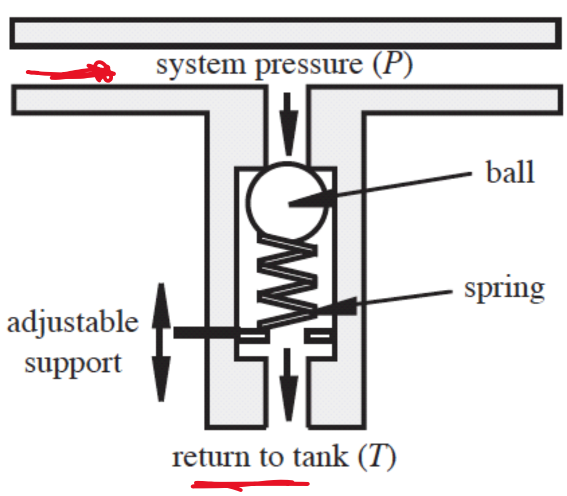
(reflected inertia)

Hydraulic actuation



① **Hydraulic Fluid** : These are typical high pressure oils
Typical pressures are 1000 - 3000 psi (Note atmospheric pressure is only 14.7 psi)
The fluids should have ① good lubrication properties to prevent wear in components ② good corrosion resistance and ③ need to be incompressible to provide rapid response.

② **Pressure regulator**

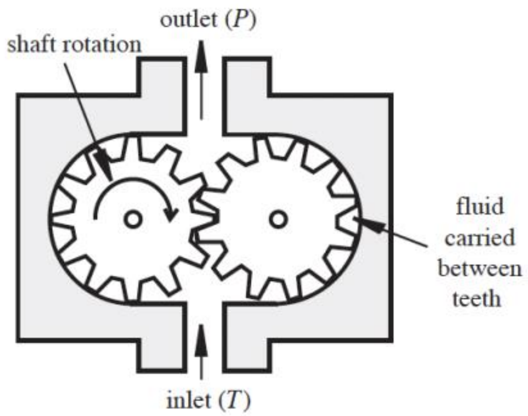


- Needed to regulate the pressure
- Spring-ball arrangement:
  By changing the spring constant the pressure set pt. can be changed.

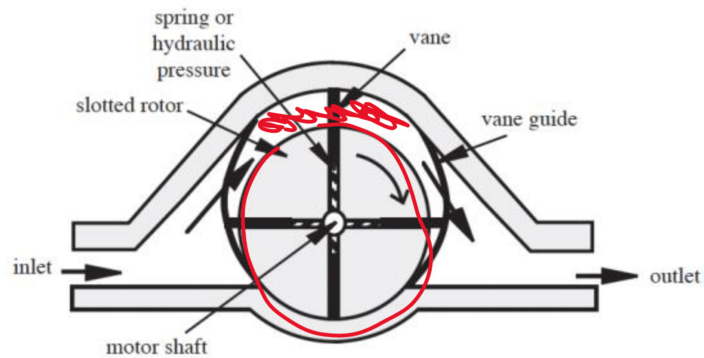
② Hydraulic pump

- Driven by electric motors or IC engines
- They deliver a fixed volume each cycle (positive displacement)
- Three pumps as shown below

(i) Gear pump

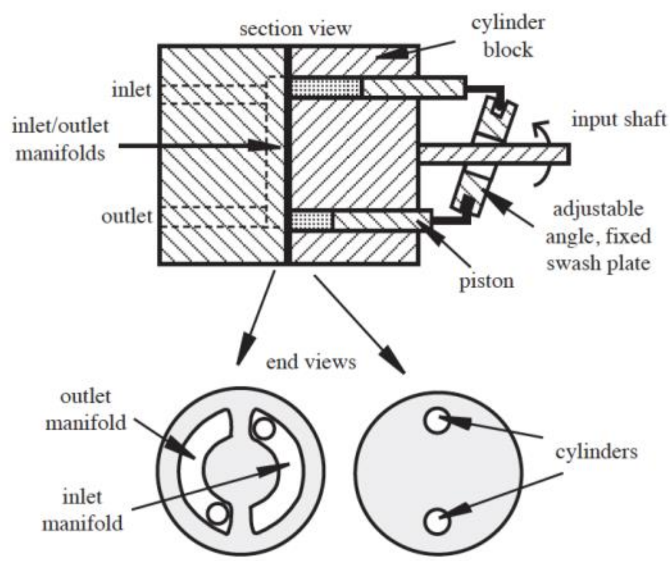


(ii) Vane pump



(iii) Piston pump:

- Inlet rotated & piston is moved up/down
- 1 half fluid is sucked in
  2 half fluid is sucked out



Pump type	Displacement	Typical pressure (psi)	Cost
Gear	Fixed	2000	Low
Vane	Variable	3000	Medium
Piston	Variable	6000	High

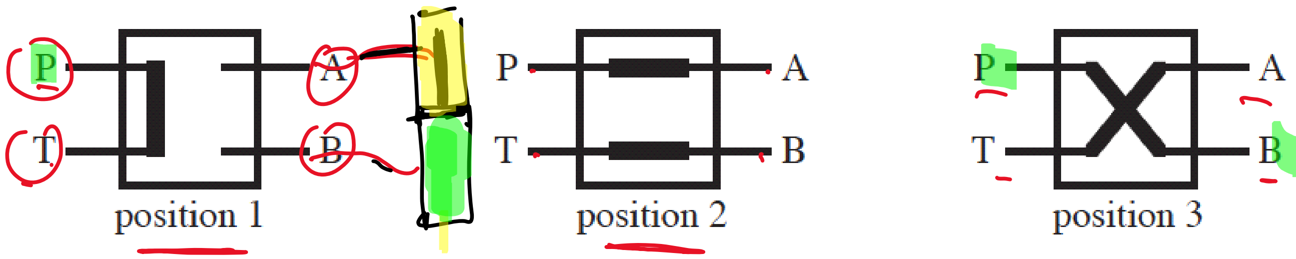
Hydraulic valves

i) infinite position valves: continuous positions to modulate the pressure

ii) finite position valves: has distinct positions, each providing different pressure and flow conditions.

inlet and outlet connections are called ports. These are denoted by x/y values where x = number of ports and y is the number of positions.

Example, 4/3 is shown below

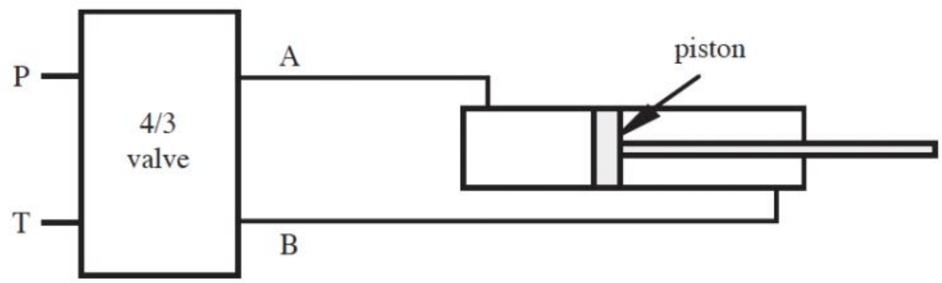


position 1: vented to the tank

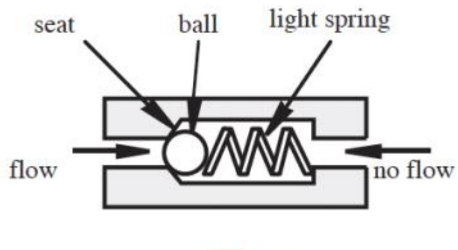
position 2: A pressurized, B vented to the tank.

position 3: B pressurized, A vented to the tank.

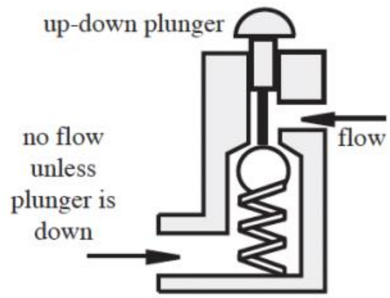
This valve is useful to control a double acting cylinder



Some example valves

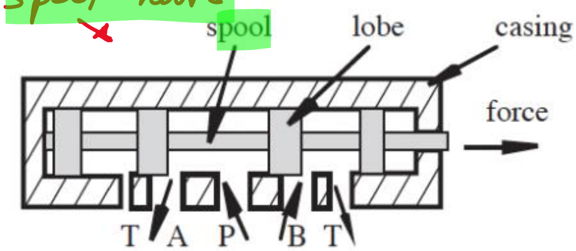


(a) check valve



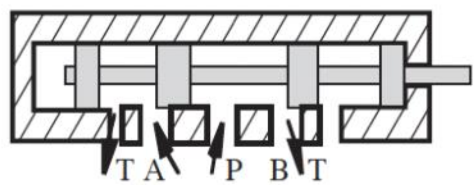
(b) poppet valve

Spool valve



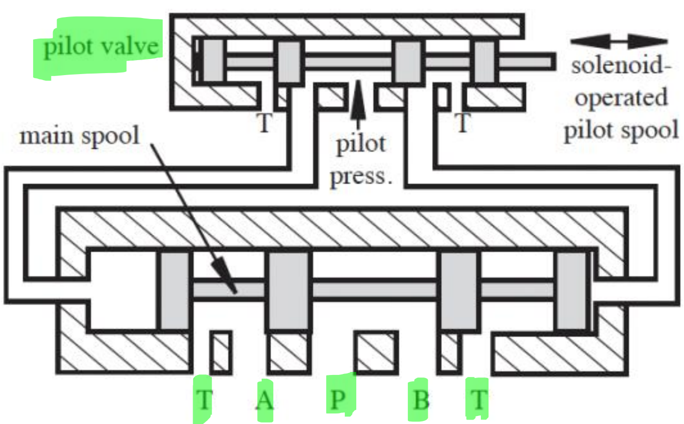
left position (P-A, B-T) position 2

A pressurized



right position (A-T, P-B) position 3

B pressurised

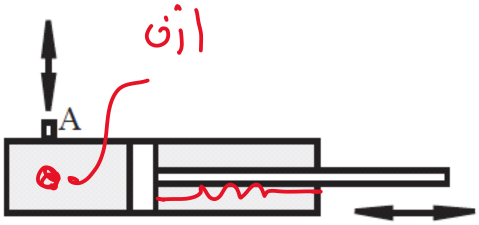


When there are large hydrodynamics forces involved, a pilot valve is added to the spool valve. A pilot valve operates at lower pressure/flow rates and hence requires less forces to actuate.

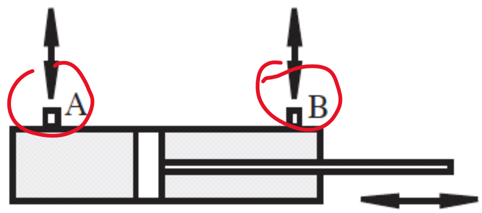
All valves shown above are ON-OFF. But there are proportional valves that allow motion proportional to mechanical input force or electrical input. When spool position is controlled by solenoid, it is called a electrohydraulic valve. When there is a position feedback to control valve position, it's a servo-valve.

a position feedback to control valve position, it's a ==servo-valve==

Hydraulic actuators



single-acting cylinder

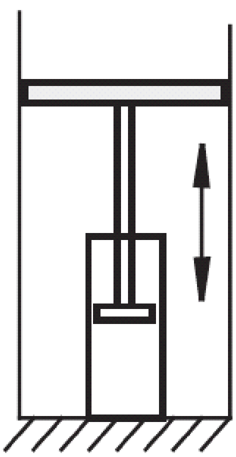


double-acting cylinder

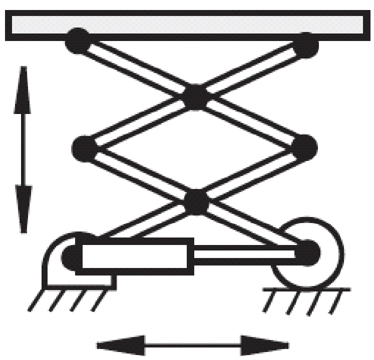
(i) Single-acting cylinder: fluid pressure pushes one way, spring restores position

(ii) Double-acting cylinder: Fluid pressure acts both ways.

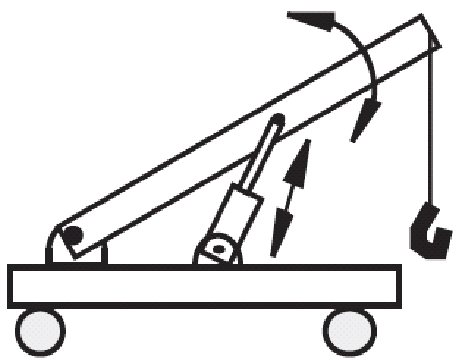
Some example applications of hydraulics.



hydraulic elevator

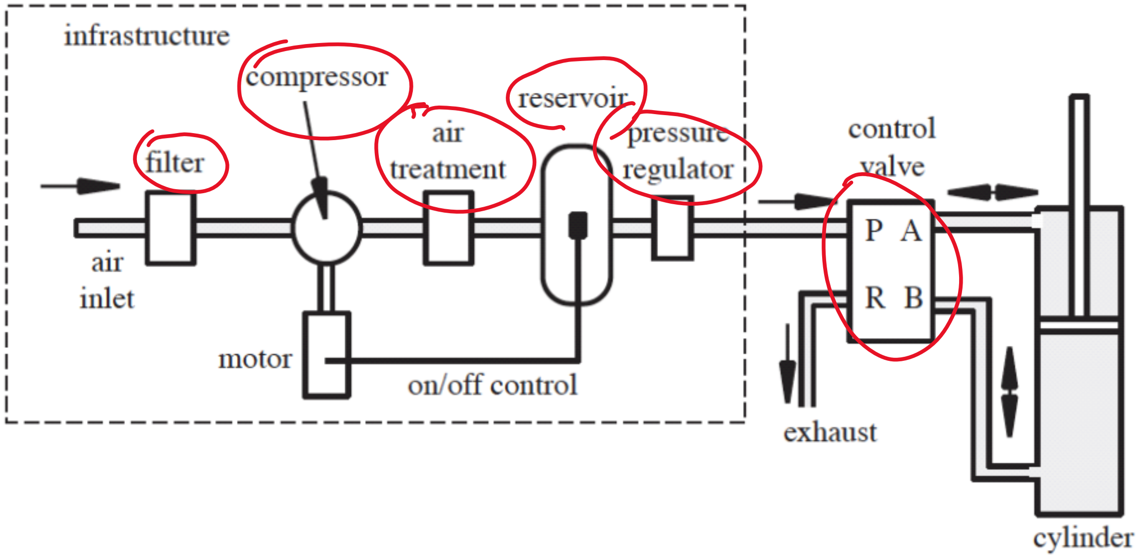


scissor jack



"cherry picker" crane

Pneumatics



Pneumatic systems are very similar to hydraulic systems with the following differences

- lower operating pressure, 70 - 150 psi
- a compressor instead of a pump.
- air treatment is needed to remove moisture and heat
- air is exhaust to the atmosphere, eliminating the need for a storage tank. Hence pneumatics is an open system unlike hydraulics which is a closed system.