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# Actuators in robotics
## Overview

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Courtesy to several authors of presentations on the web.

# What is an actuator in robotics?

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- A mechanical device for actively moving or driving something.
- Source of movement (drive), taxonomy:
  - Electric drive (motor).
  - Hydraulic drive.
  - Pneumatic drive.
  - Internal combustion, hybrids.
  - Miscellaneous: ion thruster, thermal shape memory effect, artificial muscles, etc.

# Outline of the lecture

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- Servomechanism.
- Electrical motor.
- Hydraulic drive.
- Pneumatic drive.
- Miscellaneous:
  - Artificial muscles.

# Servomechanism

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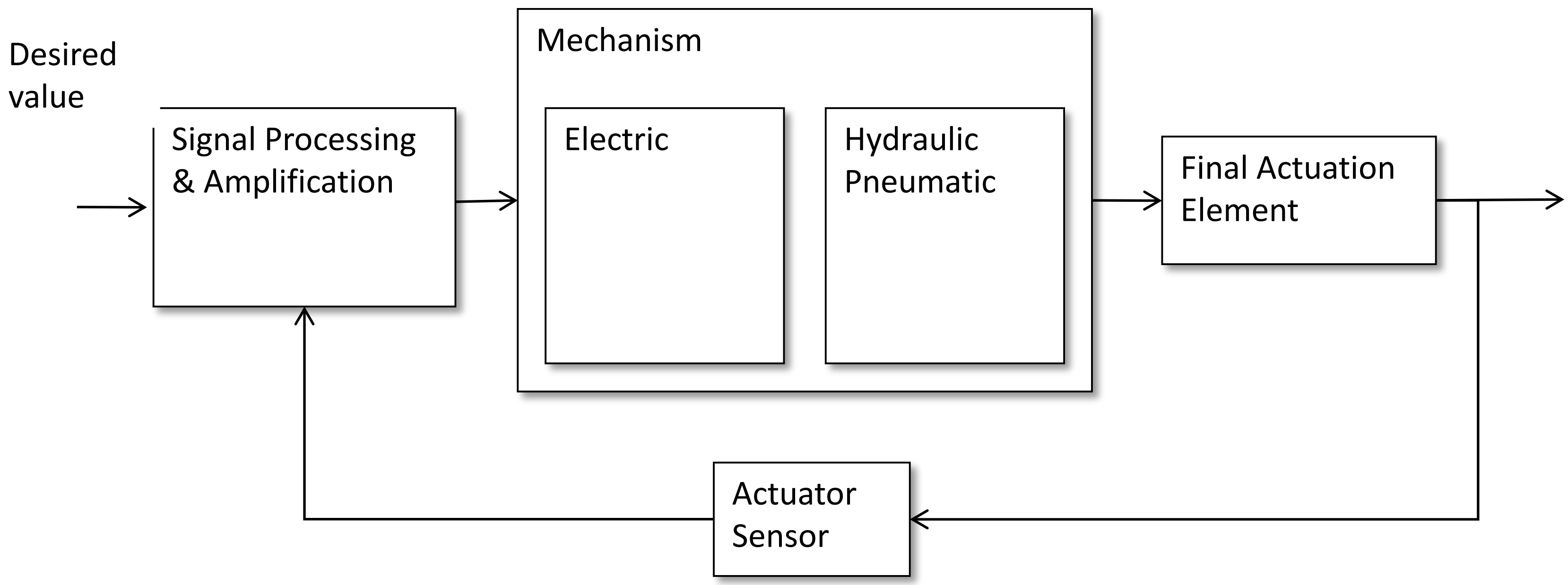
- Mechanism exploring feedback to deliver number of revolutions, position, etc.
- The controlled quantity is mechanical.



# Properties of a servo



- High maximum torque/force allows high (de)acceleration.
- Can be source of torque.
- High zero speed torque/force.
- High bandwidth provides accurate and fast control.
- Works in all four quadrants
- Robustness.

# Rotary shaft encoder

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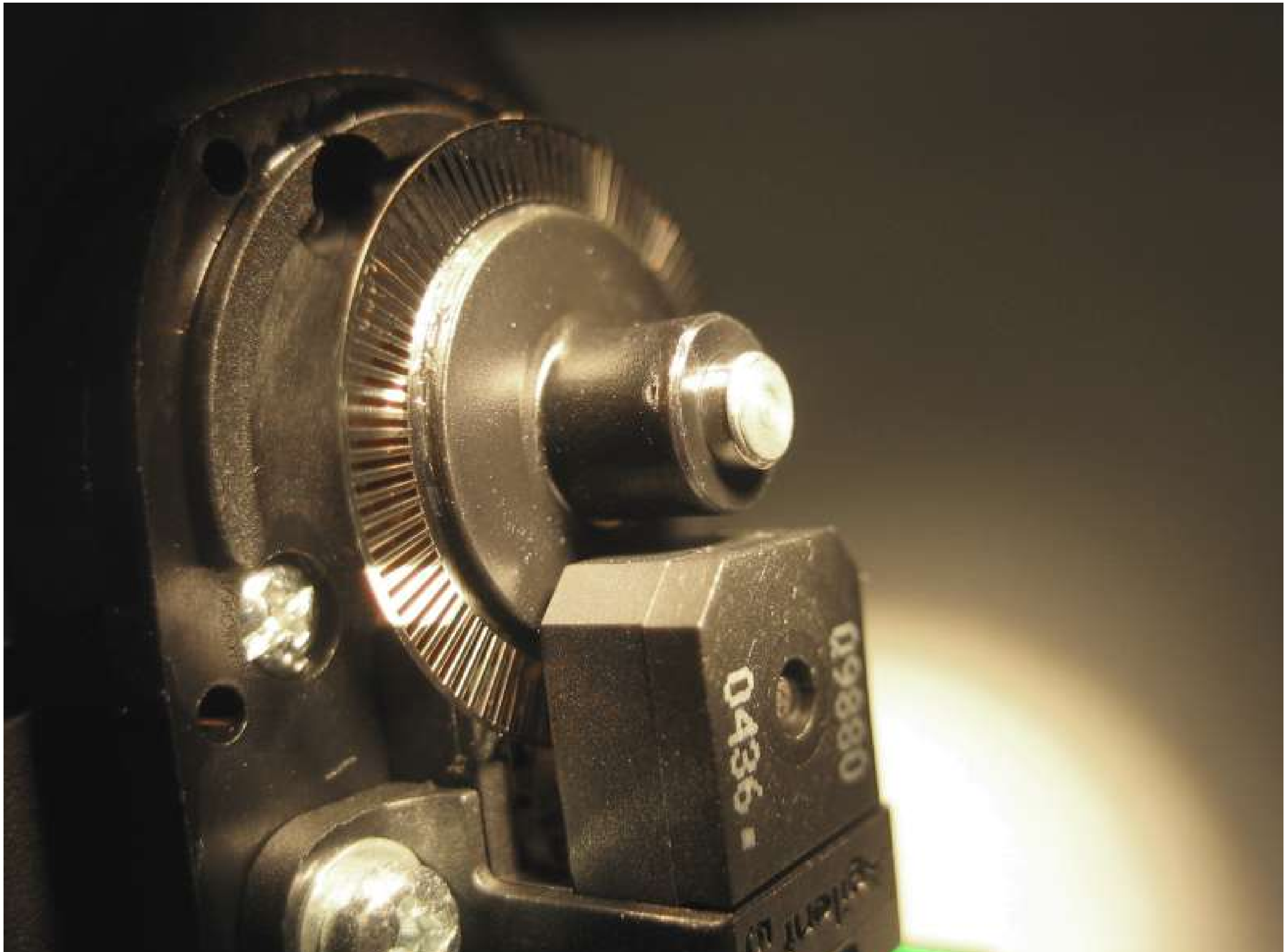

# Classification of Electric Motors

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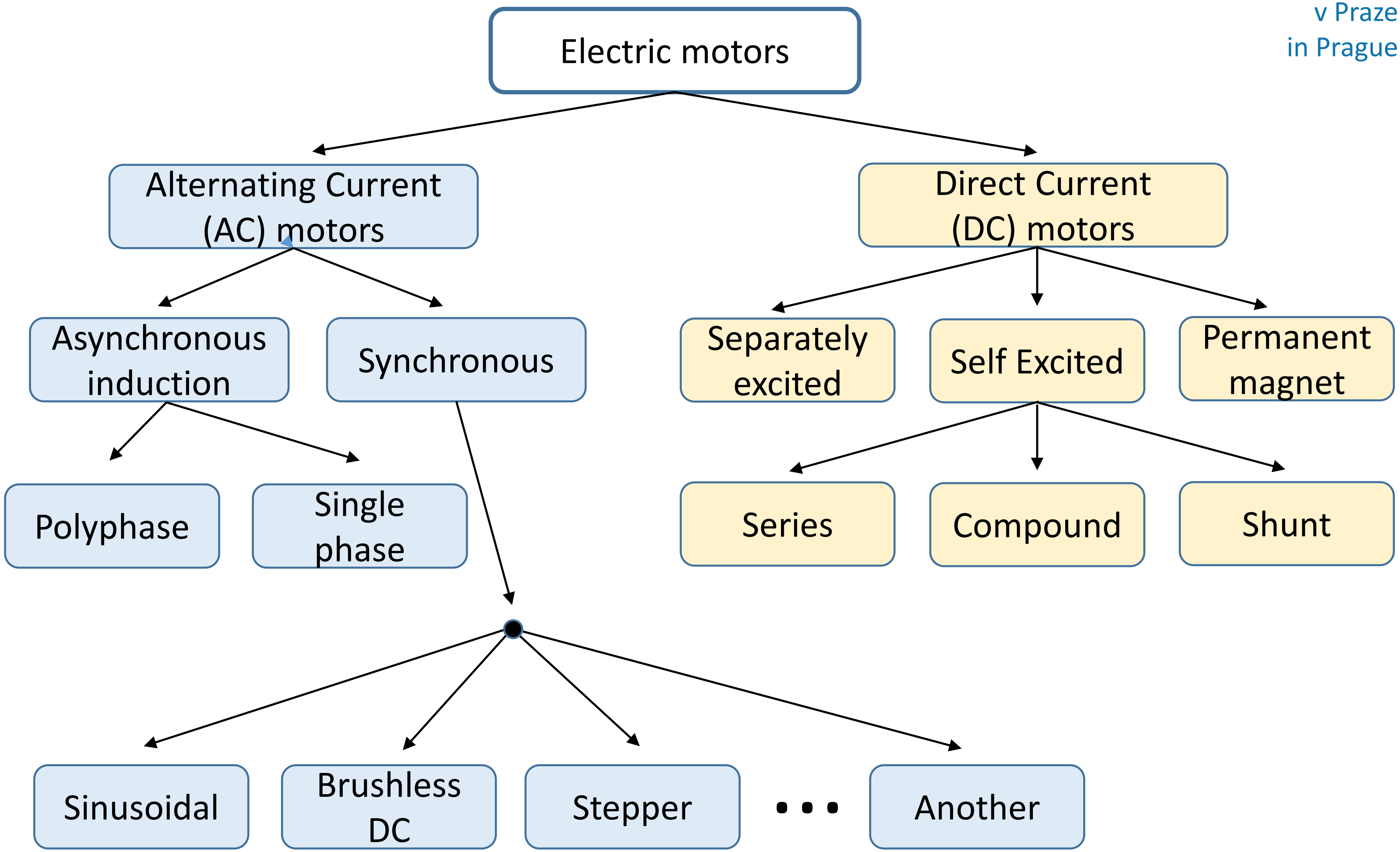

# DC motors

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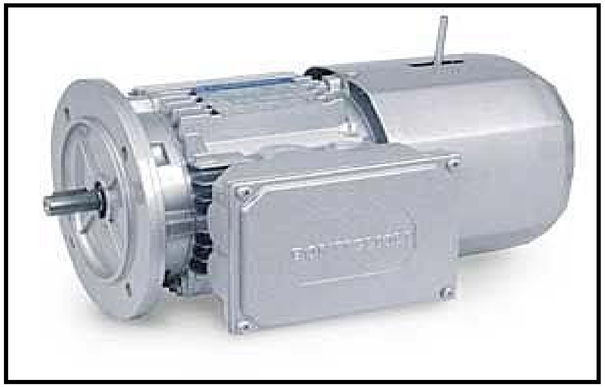
- Field pole
  - North pole and south pole
  - Receive electricity to form magnetic field
- Armature
  - Cylinder between the poles
  - Electromagnet when current goes through
  - Linked to drive shaft to drive the load
- Commutator
- Overturns current direction in armature



(Direct Industry, 1995)

# How does a DC motor work ?

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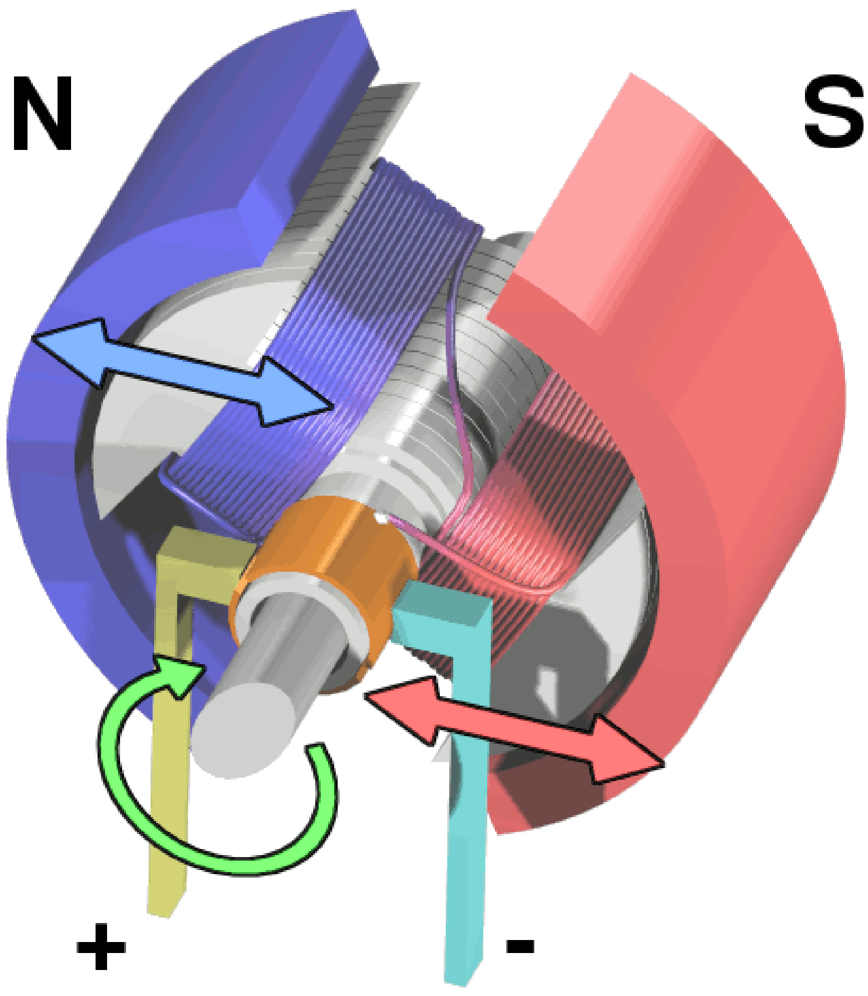

# DC motors, cont.

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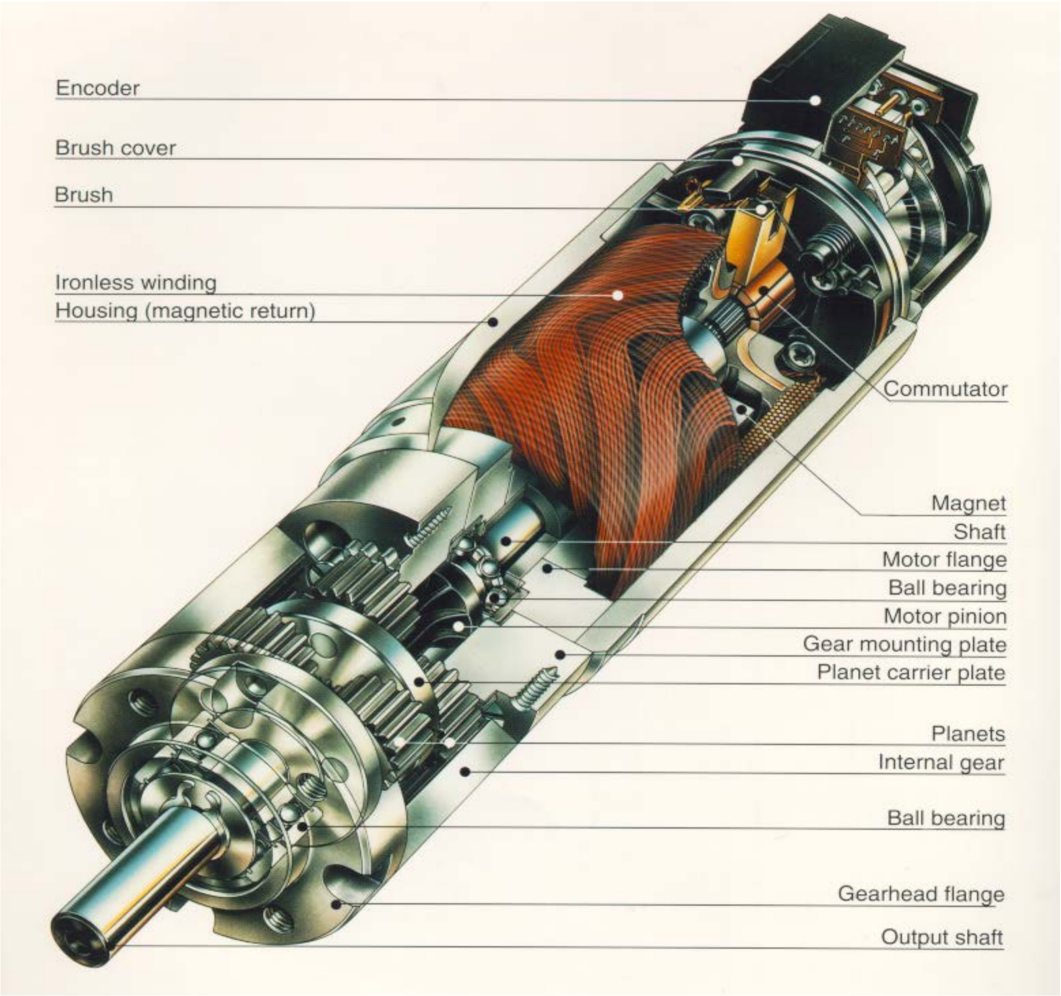
- Speed control without impact power supply quality
  - Changing armature voltage
  - Changing field current
- Restricted use
  - Few low/medium speed applications
  - Clean, non-hazardous areas
- Expensive compared to AC motors

# DC motor, a view inside

- Simple, cheap.
- Easy to control.
- 1W - 1kW
- Can be overloaded.
- Brushes wear.
- Limited overloading on high speeds.

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# DC motor control

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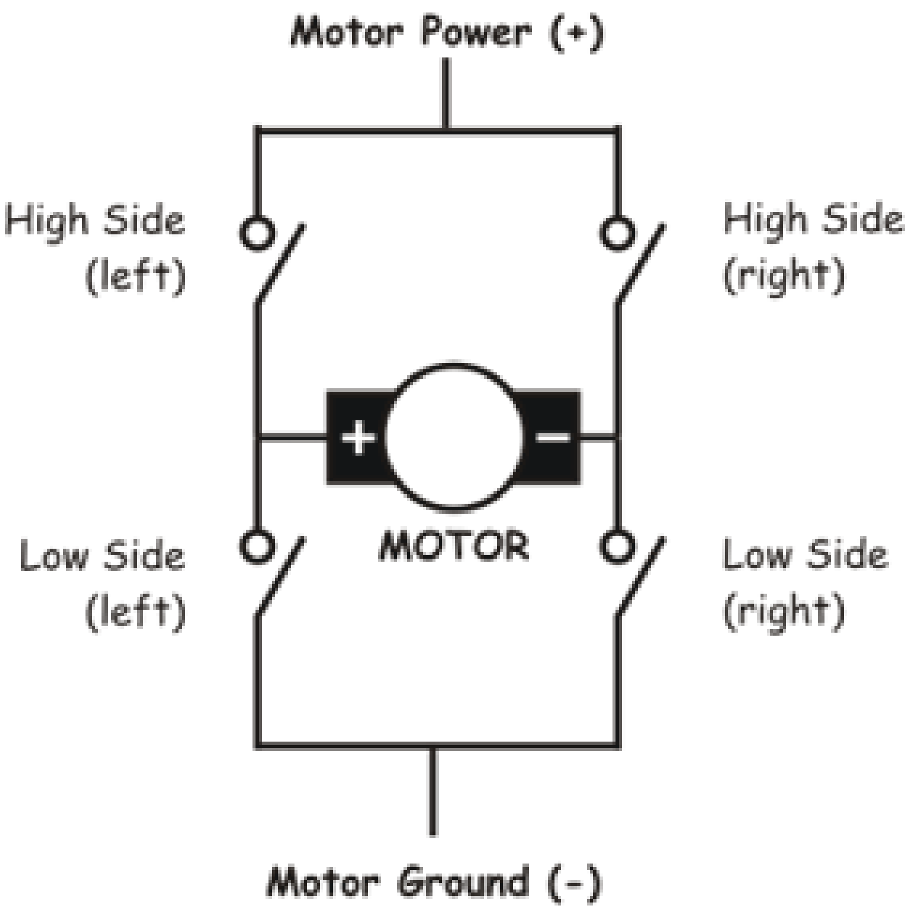
- Controller + H-bridge (allows motor to be driven in both directions).
- Pulse Width Modulation (PWM)-control.
- Speed control by controlling motor current=torque.
- Efficient small components.
- PID control.



# DC motor modeling

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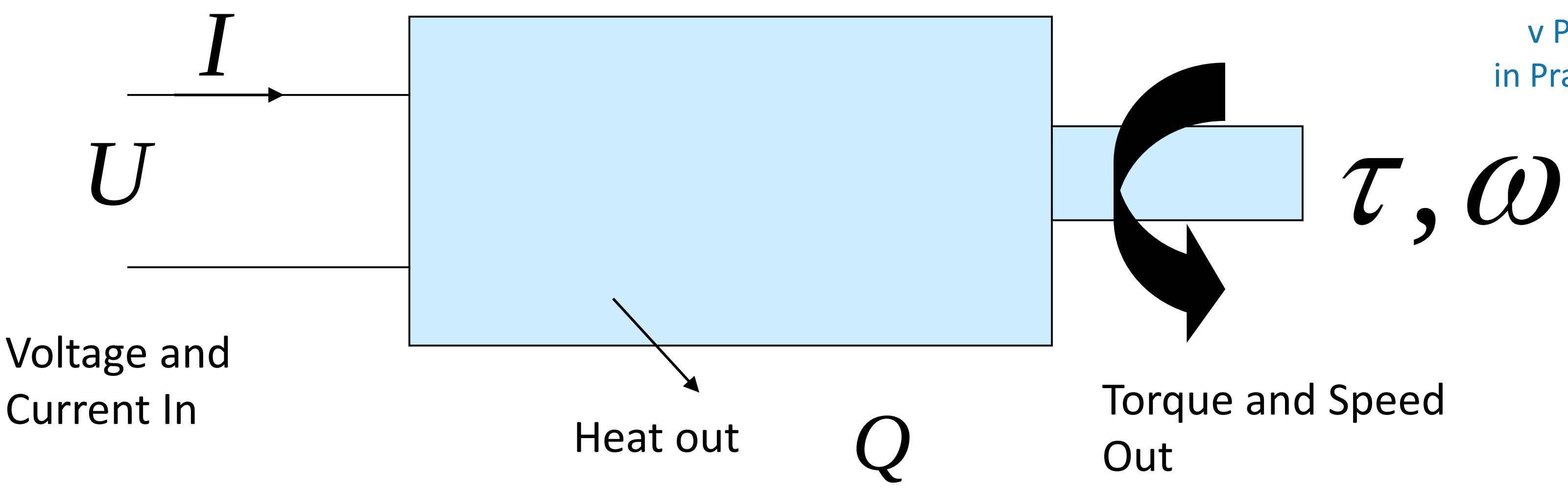



Power In = Power Out

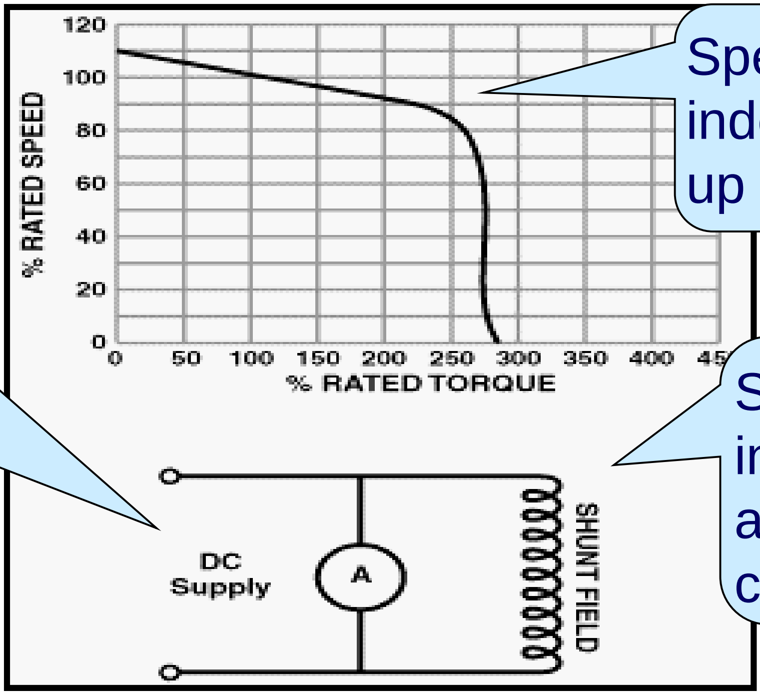
$$UI = Q + \tau\omega$$

$$\boxed{UI \cong I^2 R + \tau\omega}$$

# DC motor, shunt



- **Separately excited DC motor:** field current supplied from a separate force
- **Self-excited DC motor:** shunt motor




Speed constant independent of load up to certain torque

- Field winding parallel with armature winding
- Current = field current + armature current

Speed control: insert resistance in armature or field current

(Rodwell Int. Corporation, 1999)

# DC motor: series motor

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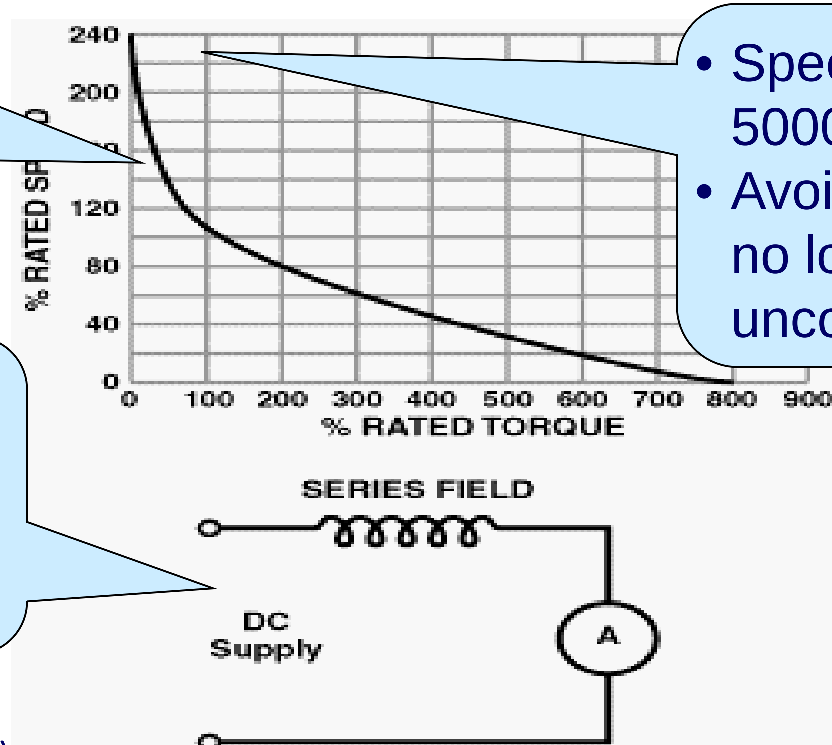
## Self-excited DC motor: series motor

Suited for high starting torque: cranes, hoists




- Speed restricted to 5000 RPM
- Avoid running with no load: speed uncontrolled

- Field winding in series with armature winding
- Field current = armature current

(Rodwell Int. Corporation, 1999)

# DC compound motor

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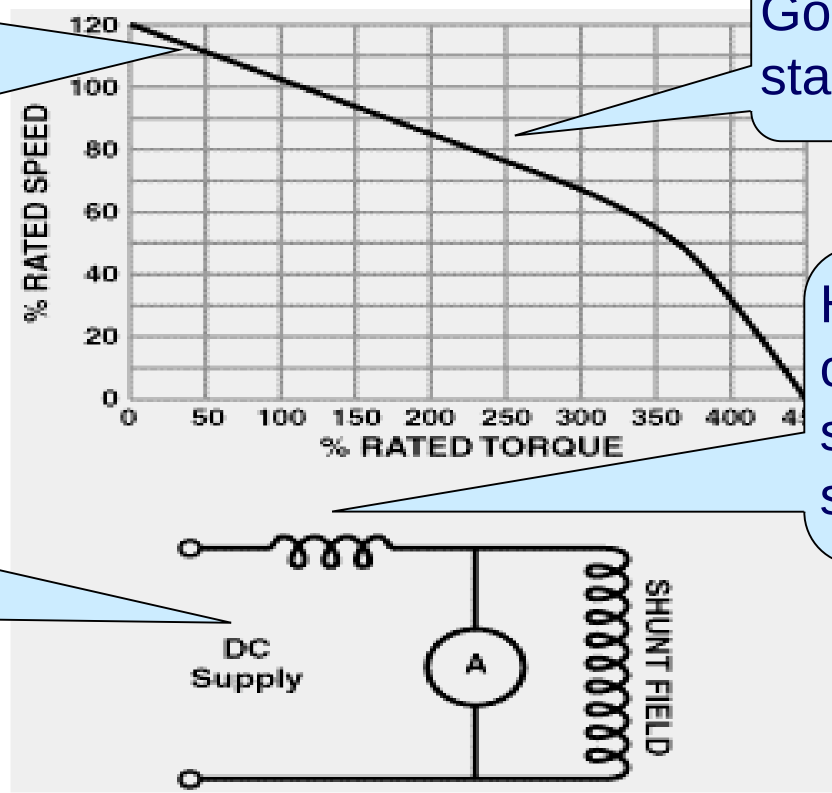
Suited for high starting torque if high % compounding: cranes, hoists

Good torque and stable speed




Higher % compound in series = high starting torque

Field winding in series and parallel with armature winding

# Digital control of DC motors

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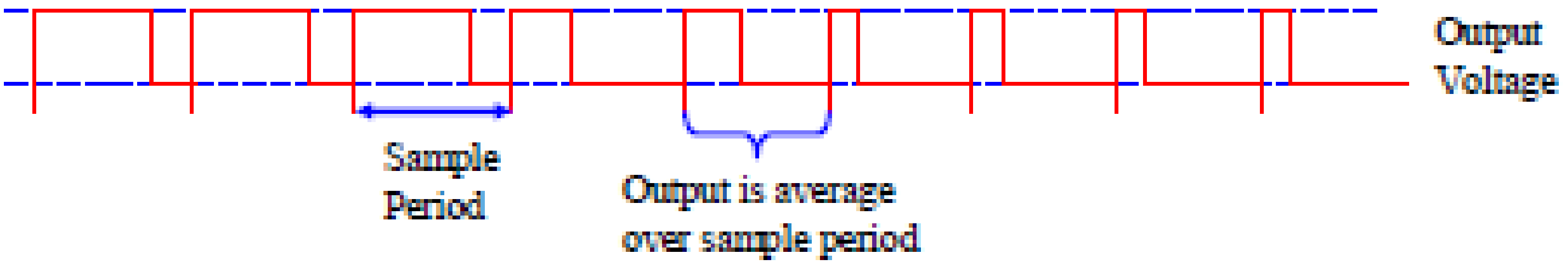
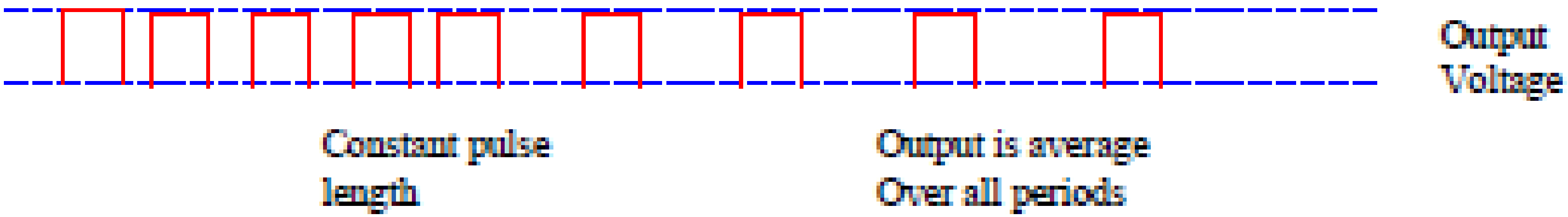
## Pulse-Width-Modulated (PWM)



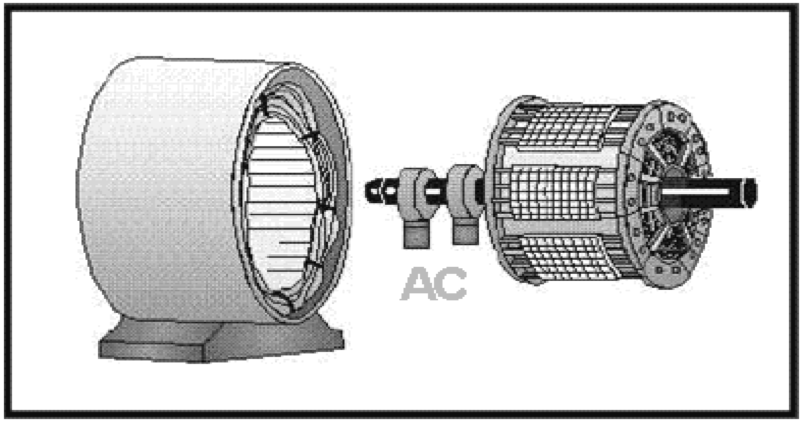

## Pulse-Rate-Modulated (PRM)



# AC motor



- Electrical current reverses direction
- Two parts: stator and rotor
  - Stator: stationary electrical component
  - Rotor: rotates the motor shaft
- Speed difficult to control because it depends on current frequency
- Two types
  - Synchronous motor
  - Induction motor



# AC motor inventor

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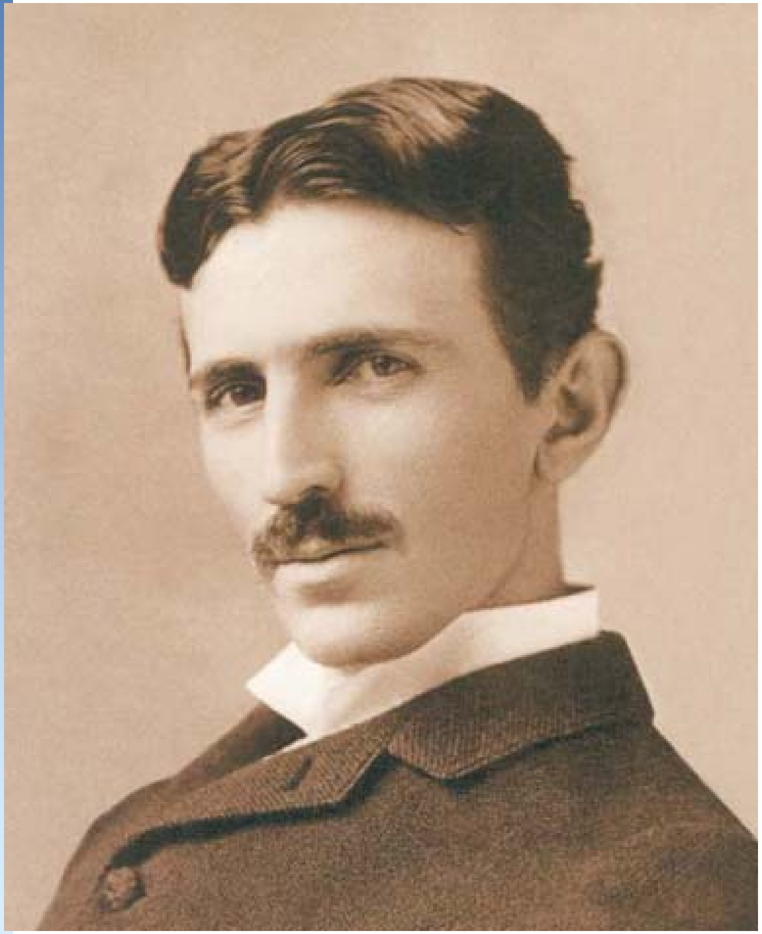

Nikola Tesla

# AC synchronous motors

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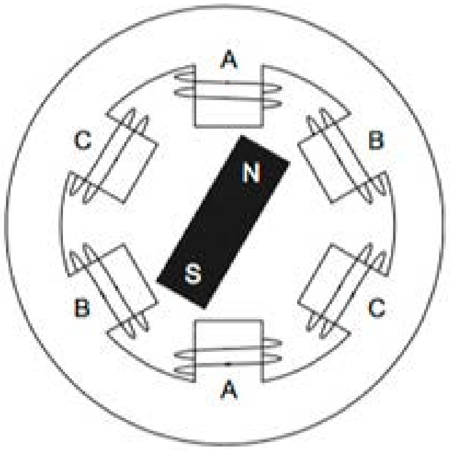
- Constant speed fixed by system frequency
- DC for excitation and low starting torque: suited for low load applications
- Can improve power factor: suited for high electricity use systems
- Synchronous speed (Ns):

$$Ns = 120\, f / P$$

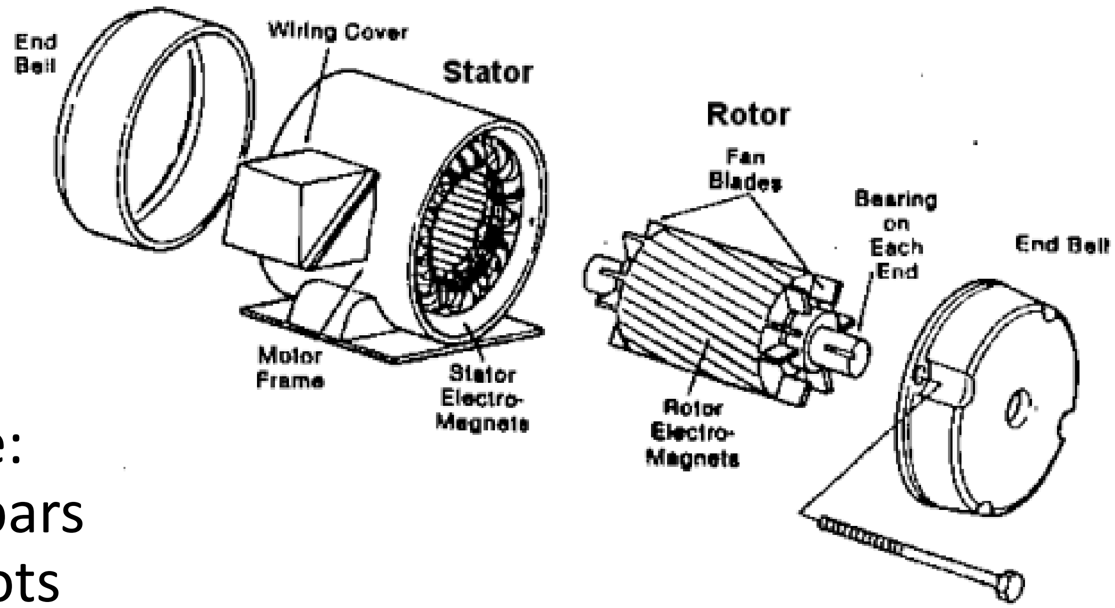
$f$ = supply frequency
$P$ = number of poles




Three-phase synchronous motor with a single permanent magnet rotor.

# AC induction motor, components






- Rotor
  - Squirrel cage: conducting bars in parallel slots
  - Wound rotor: 3-phase, double-layer, distributed winding
- Stator
  - Stampings with slots to carry 3-phase windings
  - Wound for definite number of poles

# How induction motors work ?

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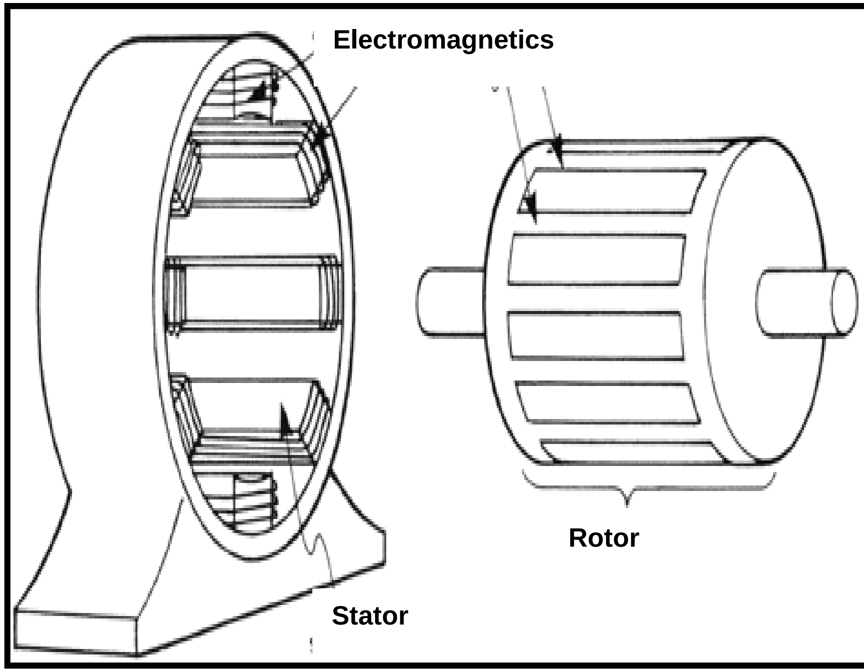
- Electricity supplied to the stator.
- Magnetic field generated that moves around rotor.
- Current induced in rotor.
- Rotor produces second magnetic field that opposes stator magnetic field.
- Rotor begins to rotate.



# AC induction motor, a view inside

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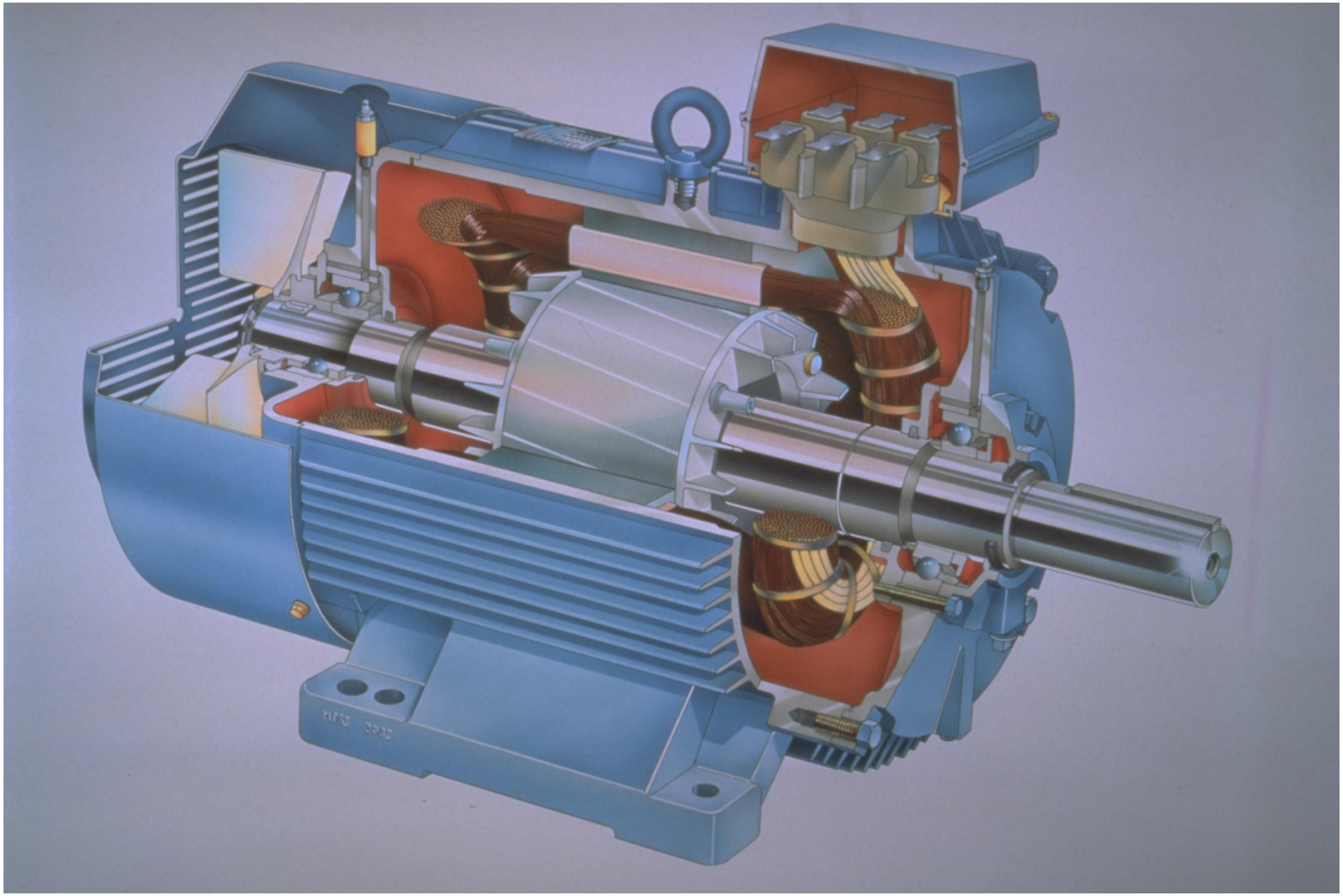

# AC induction motors, properties

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Disadvantages:

- About 7x overload current at start.
- Needs a frequency changer for control.

Advantages:

- Simple design, cheap
- Easy to maintain
- Direct connection to AC power source

Advantages (cont):

- Self-starting.
- 0,5kW – 500kW.
- High power to weight ratio
- High efficiency: 50 – 95%

# Induction motor, speed and slip

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- Motor never runs at synchronous speed but lower “base speed”
- The difference is “slip”
- Install slip ring to avoid this
- Calculate % slip:

$$\% \text{ Slip} = \frac{Ns - Nb}{Ns} \times 100$$

Ns = synchronous speed in RPM
Nb = base speed in RPM

# AC Induction motor load, speed, torque relationship

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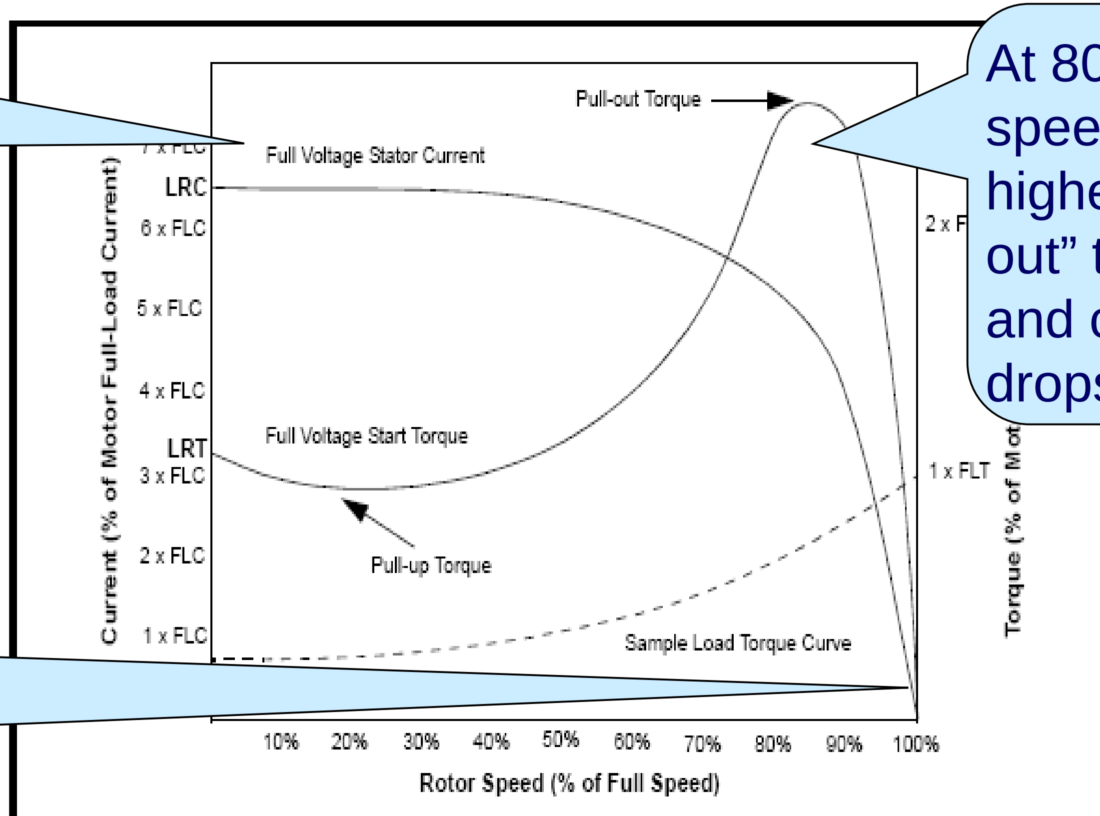
At start: high current and low “pull-up” torque




At 80% of full speed: highest “pull-out” torque and current drops

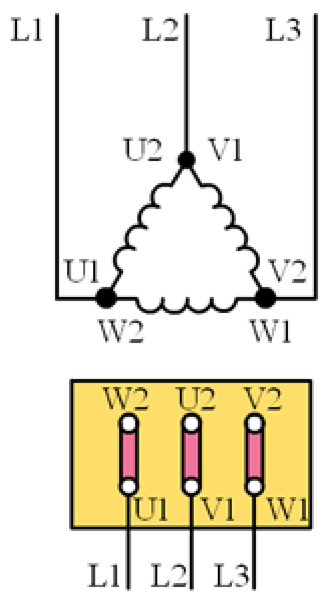
At full speed: torque and stator current are zero

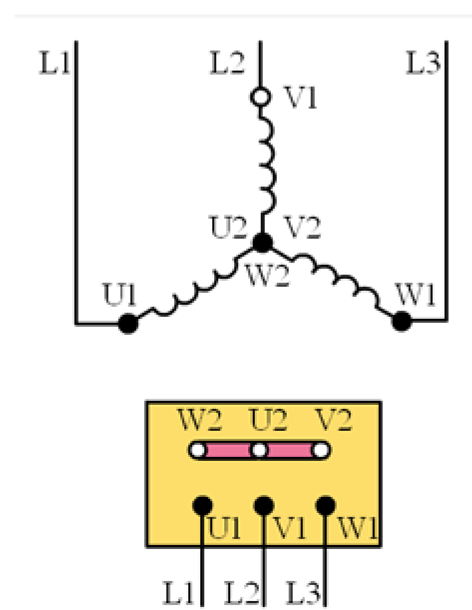
# Delta Δ – star Y



- Inter-phase (L-L) voltage 400 V.
- The inrush current can be too large (~7 times the nominal current).

- Phase-ground (L-N) voltage 230 V.
- YΔ starting reduces the inrush current.




*Courtesy: Ivo Novák, images*

# Single phase induction motor



- One stator winding.
- Single-phase power supply.
- Squirrel cage rotor.
- Use several tricks to start, then transition to an induction motor behavior.
- Up to 3 kW applications.
- Household appliances: fans, washing machines, dryers, airconditioners.
- Lower efficiency: 25 – 60 %
- Often low starting torque.

# Single-phase induction motor

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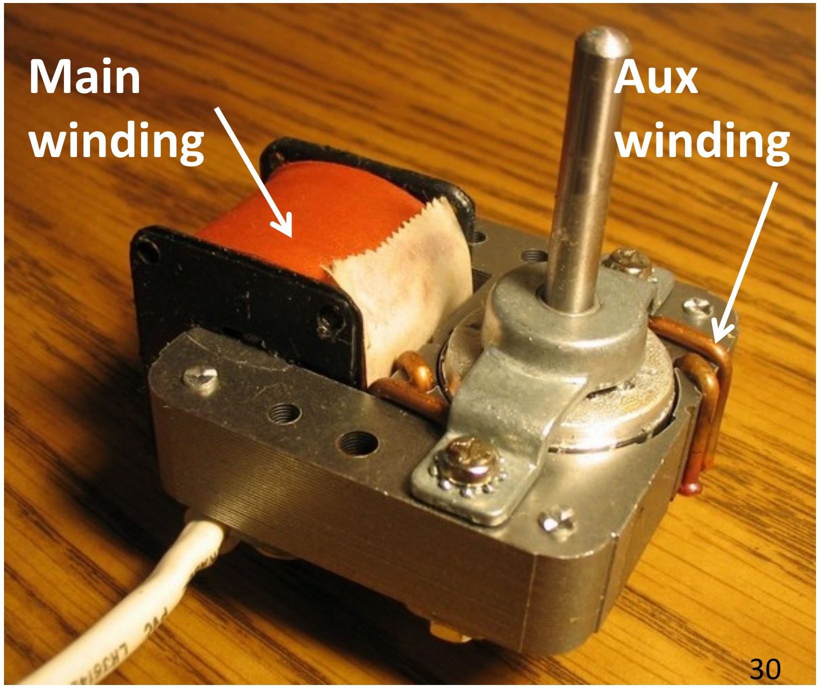
- Three-phase motors produce a rotating magnetic field.
- When only single-phase power is available, the rotating magnetic field must be produced using other means.
- Two methods to create the rotating magnetic field are usually used:
  1. Shaded-pole motor.
  2. Split-phase motor.

# Ad 1. Shaded-pole motor



- A small squirrel-cage motor with an auxiliary winding composed of a copper ring or bar.
- Current induced in this coil induce a 2nd phase of magnetic flux.
- Phase angle is small $\Rightarrow$ only a small starting torque compared to torque at full speed.

- Used in small appliances as electric fans, drain pumps of a washing machine, dishwashers.



# Ad 2. Split-phase motor (1)



- Has a startup winding separate from the main winding. Fewer turns of smaller wire than the main winding, so it has a lower inductance (L) and higher resistance (R).
- The lower L/R ratio creates a small phase shift, not more than about 30 degrees.
- At start, the startup winding is connected to the power source via a centrifugal switch, which is closed at low speed.
- The starting direction of rotation is given by the order of the connections of the startup winding relative to the running winding.

# Ad 2. Split-phase motor (2)

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- Once the motor reaches near operating speed, the centrifugal switch opens, disconnecting the startup winding from the power source.
- The motor then operates solely on the main winding.
- The purpose of disconnecting the startup winding is to eliminate the energy loss due to its high resistance.
- Commonly used in major appliances such as air conditioners and clothes dryers.

# Ad 2. Split-phase motor (3)

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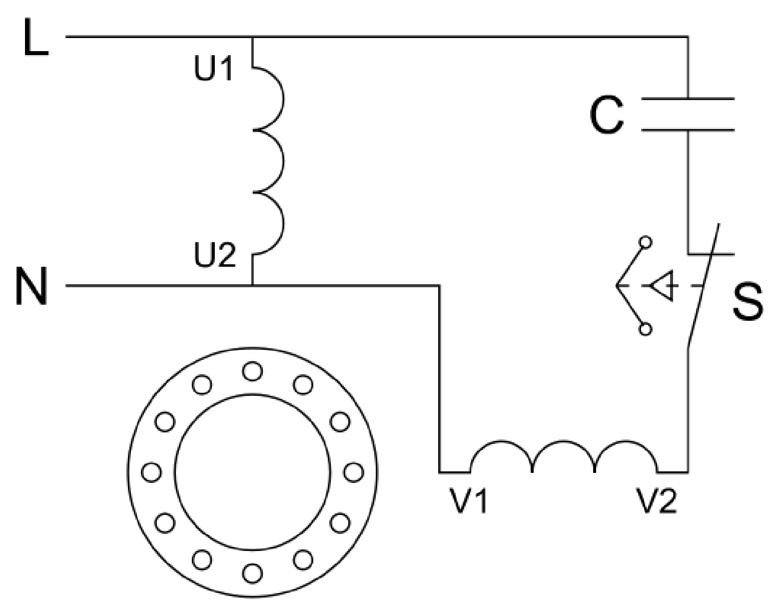
- A capacitor start motor is a split-phase induction motor with a starting capacitor inserted in series with the startup winding.
- An LC circuit produces a greater phase shift (and so, a much greater starting torque) than a split-phase motor.



# Voice coil motor

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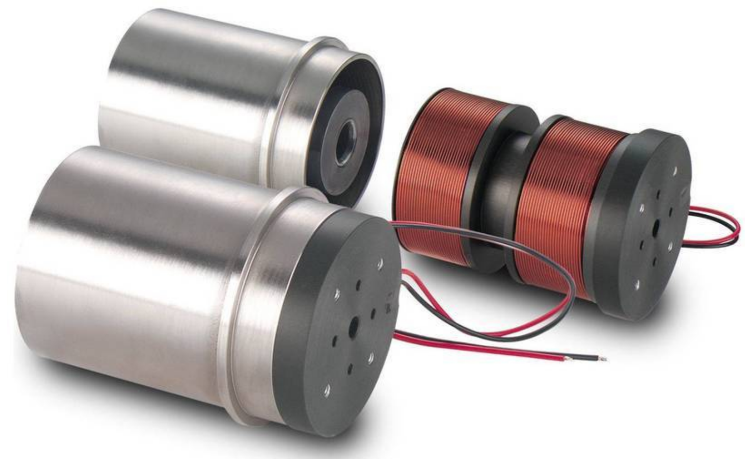
- The name comes form the original use in loudspeakers.
- Either moving coil or moving magnet.
- Used for proportional or tight servomechanisms, where the speed is of importance.
- E.g. in a computer disc drive, gimbal or other oscillatory applications.



# Linear electric motors

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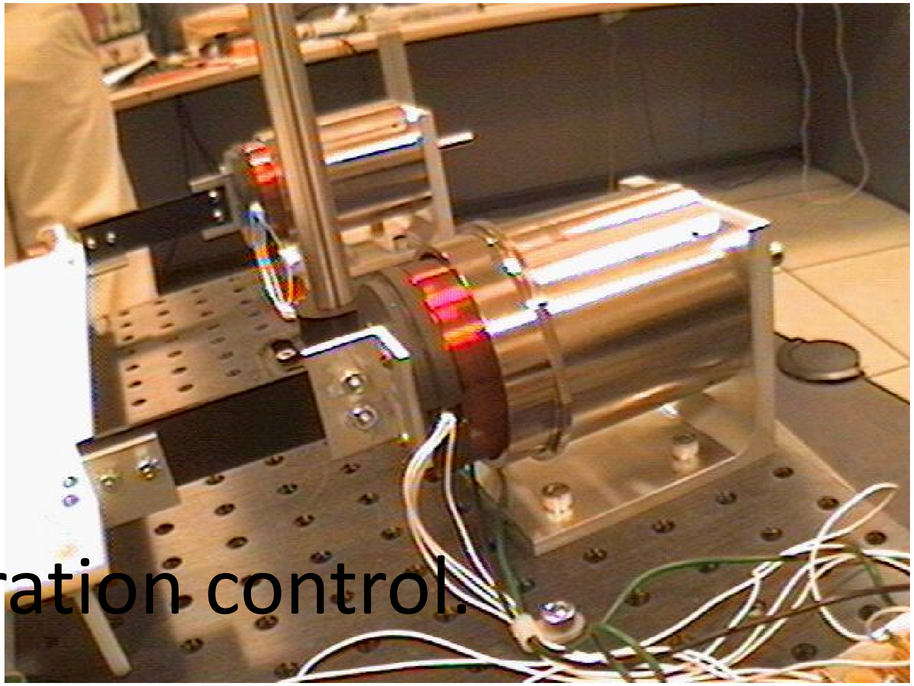
- There are some true linear magnetic drives.
  - BEI-Kimco voice coils:
  - Up to 30 cm travel
  - 100 lbf
  - > 10 g acceleration
  - 2.5 kg weight
  - 500 Hz corner frequency.



- Used for precision vibration control.

# Tubular linear motor

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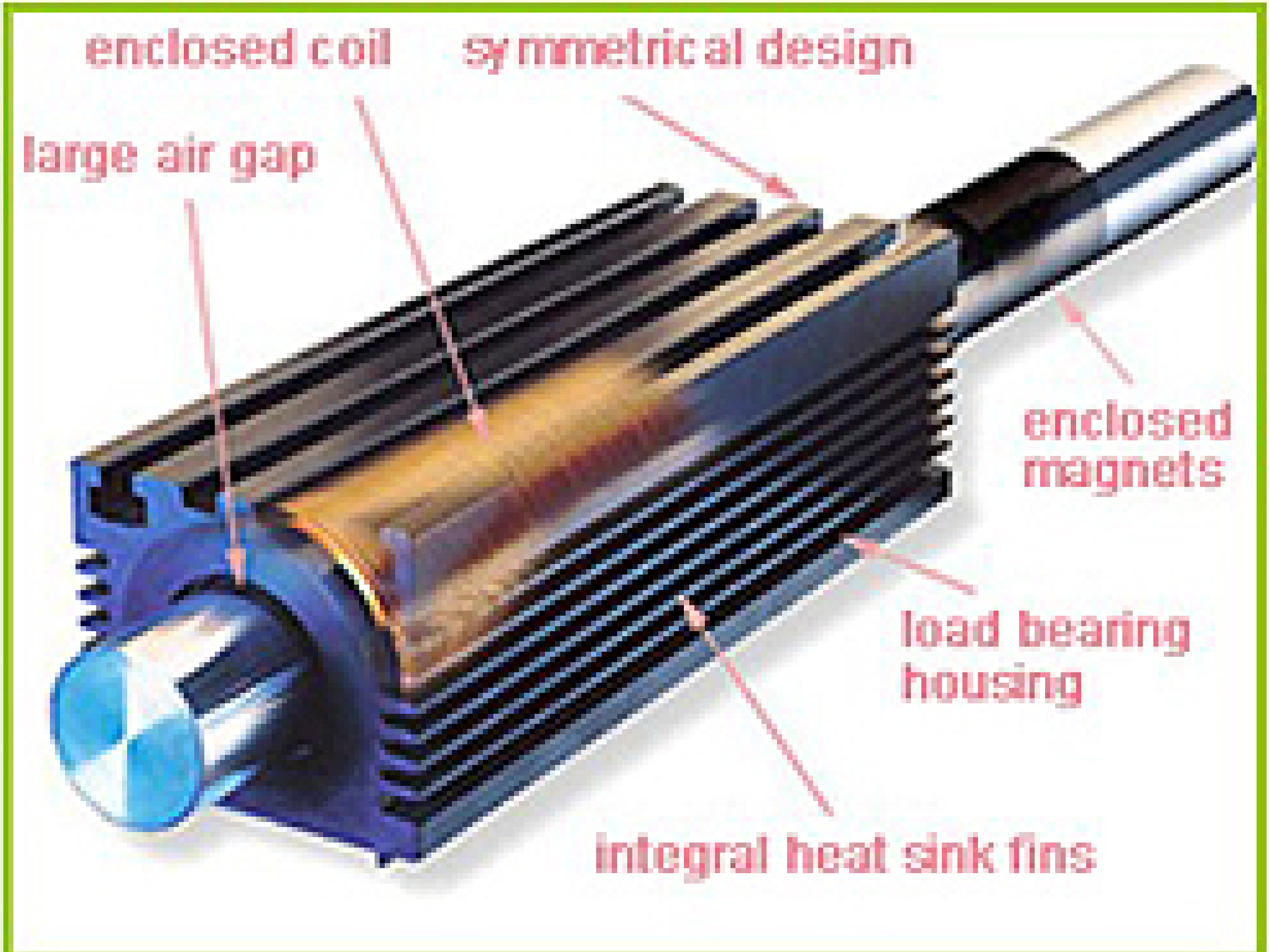


Copley Controls Corp.
Copley Motion Systems LLC

# MODELS XTB3804-3810 SERVOTUBE COMPONENTS

CE

### Force

- Peak: 744 - 1860 N
- Continuous: 137 - 276N

### Maximum Velocity

- Up to 9.4 m/s

### Feedback

- Built-in position sensor
- 1V pk-pk sin/cos
- 25 micron repeatability

### Range of motion

- Travel lengths up tp 1362 mm

### Dimensions

- W x H: 70 x 122mm
- Rod diameter: 38mm

ServoTube delivers the speed of a belt-drive system with the clean reliability of a linear forcer at a price unprecedented in the industry. Familiar form factor, integral position feedback and large air gap make installation simple.

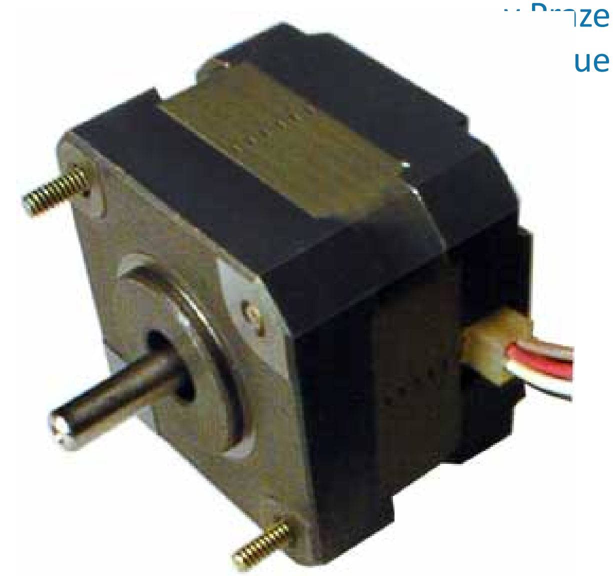
The ServoTube forcer components consist of an IP67 rated forcer and a sealed stainless steel thrust rod enclosing rare-earth magnets. Four models deliver a continuous force range of 137~276 N (31~62 lb) with peak forces up to 1860 N (418 lb). A

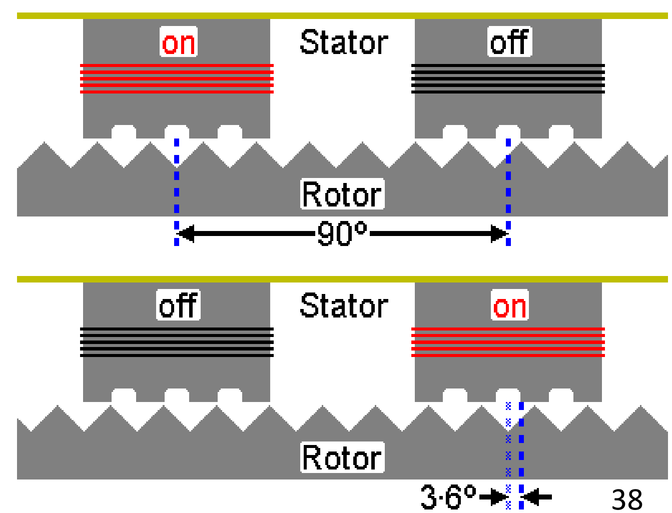
ServoTube is an ideal OEM solution for easy integration into pick-and-place gantries and general purpose handling machines. The load is mounted directly to the forcer typically supported by a single bearing rail. The Thrust Rod is mounted at both ends, similar to a ballscrew. A large air gap reduces alignment constraints.

The tubular forcer has superior thermal efficiency, radiating heat uniformly. High duty cycles are possible without the need for forced-air or water cooling.

# Stepper Motors

- A sequence of (3 or more) poles is activated in turn, moving the stator in small “steps”.
- Very low speed / high angular precision is possible without reduction gearing by using many rotor teeth.
- Can also perform a “microstep” by activating both coils at once.





# Driving stepper motors

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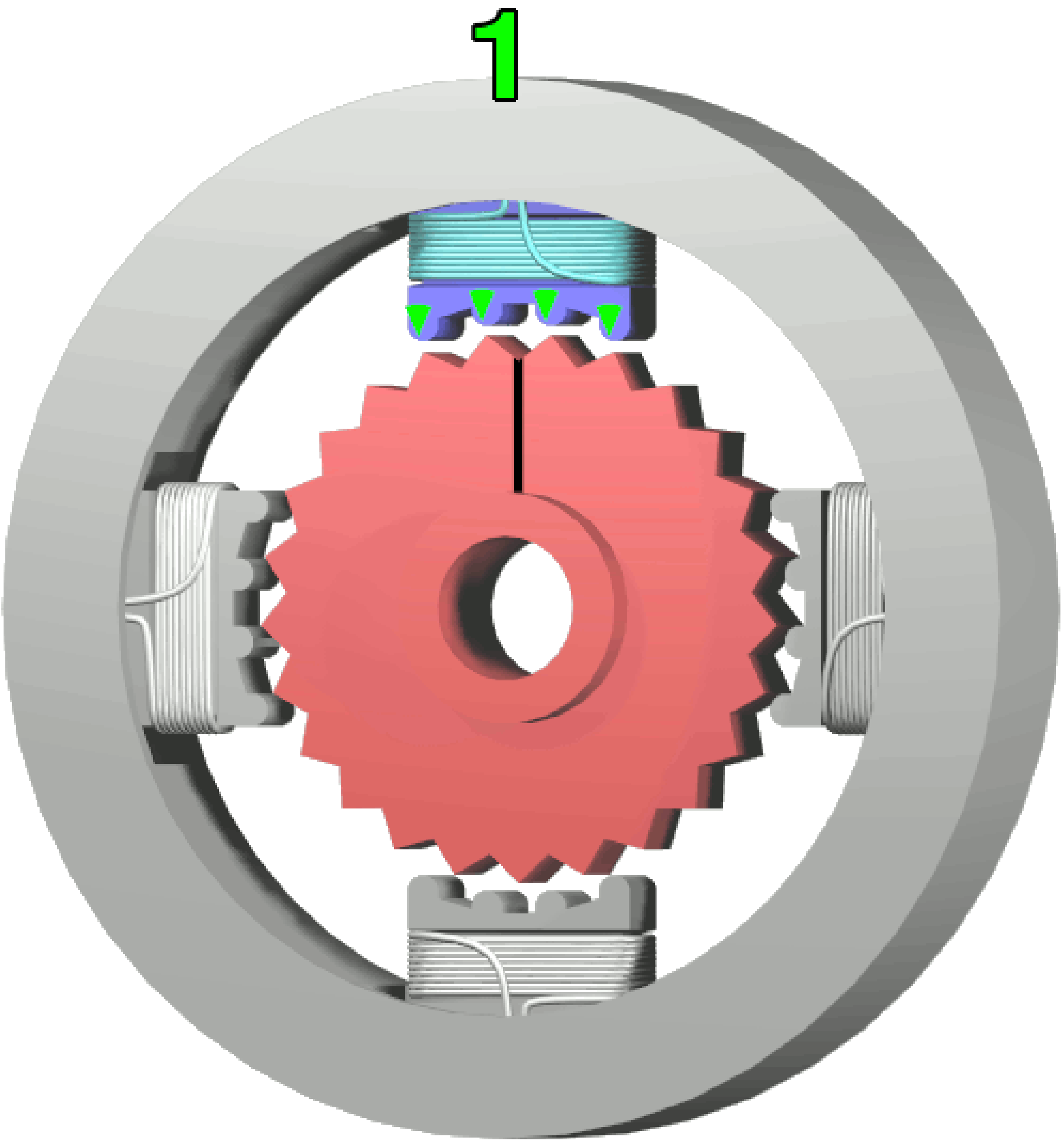
- Signals to the stepper motor are binary, on-off values (not PWM).
- In principle easy: activate poles as A B C D A … or A D C B A …Steps are fixed size, so no need to sense the angle! (open loop control).
- In practice, acceleration and possibly jerk must be bounded, otherwise motor will not keep up and will start missing steps (causing position errors).
- Driver electronics must simulate inertia of the motor.

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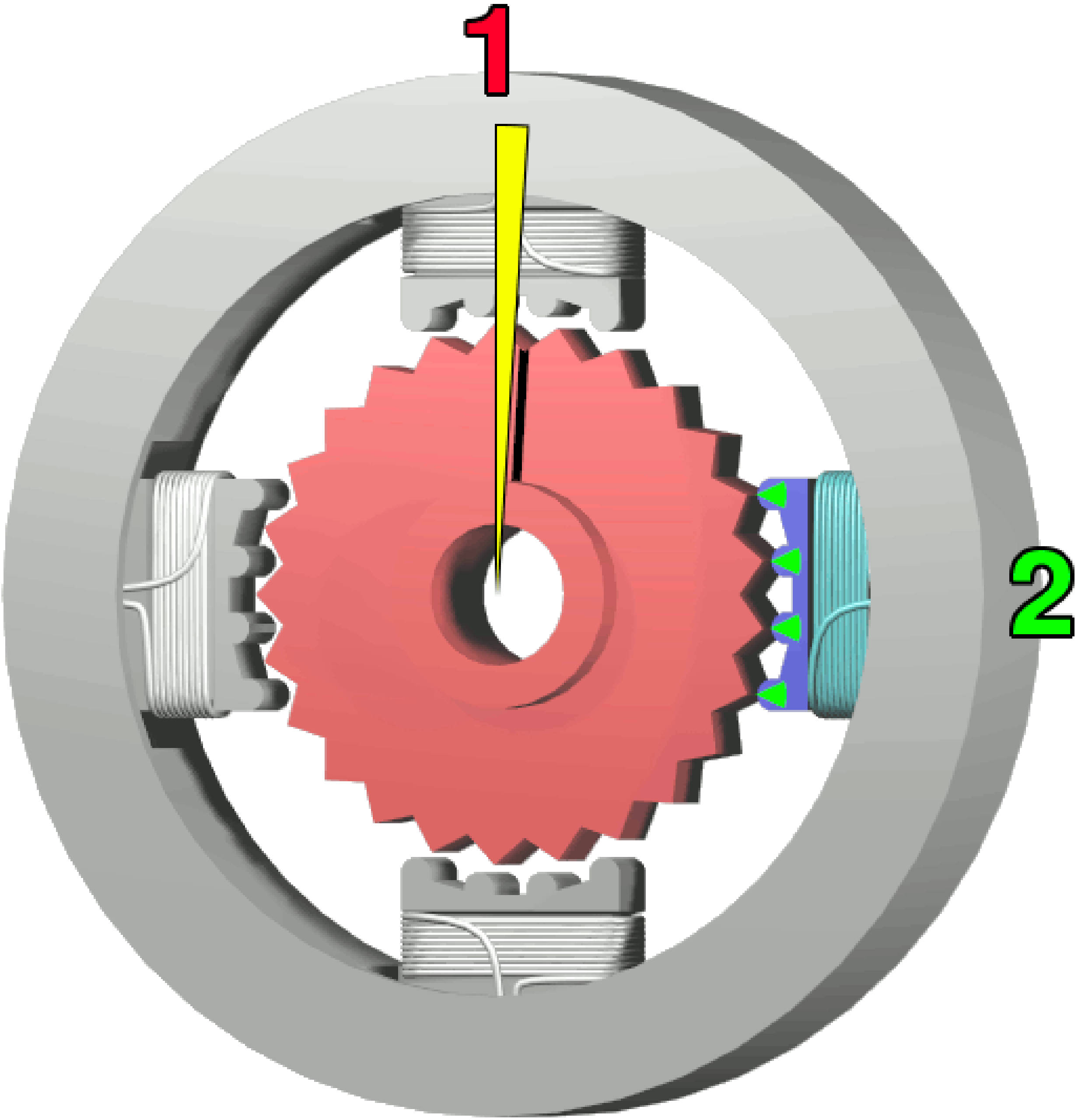


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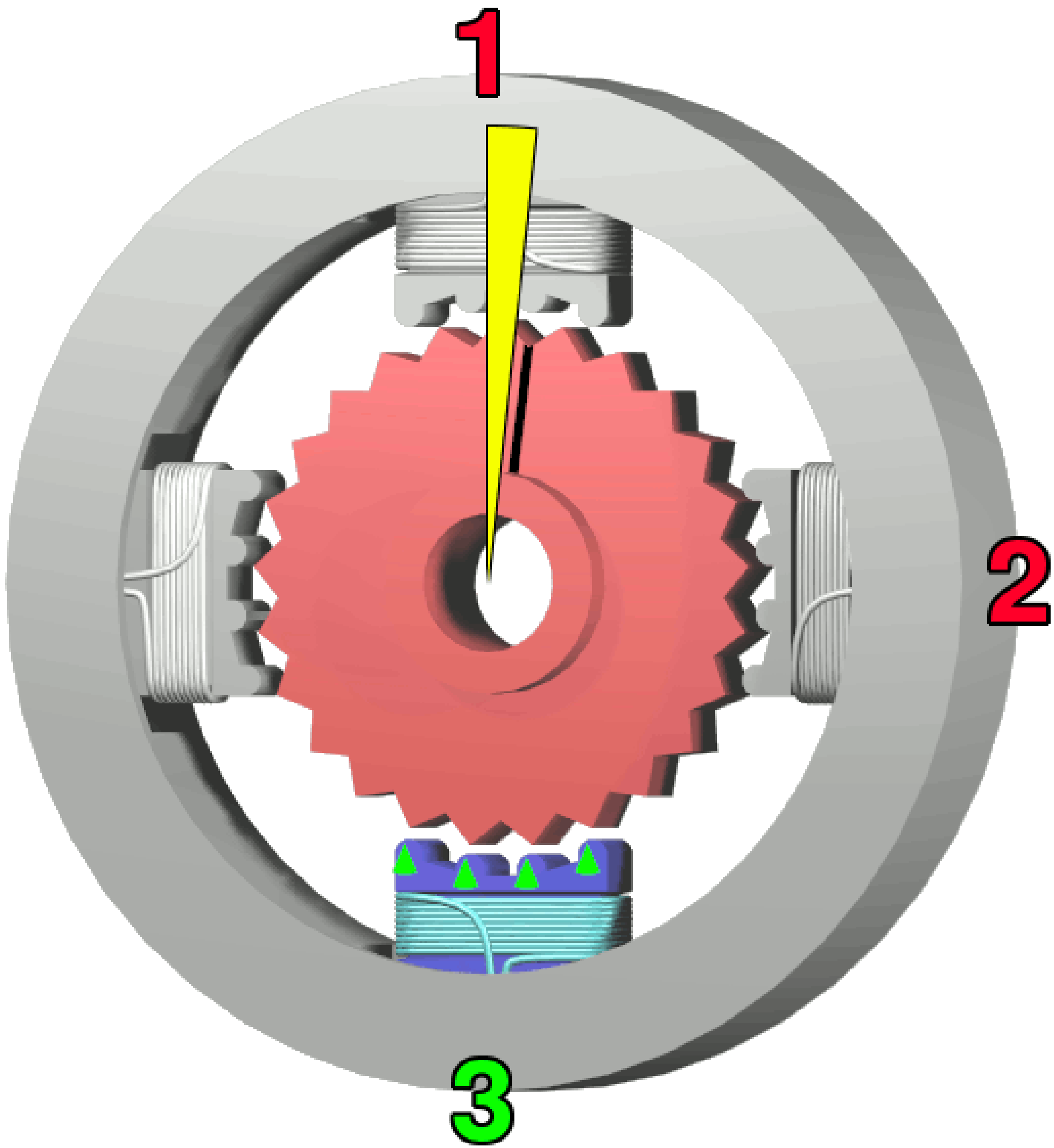
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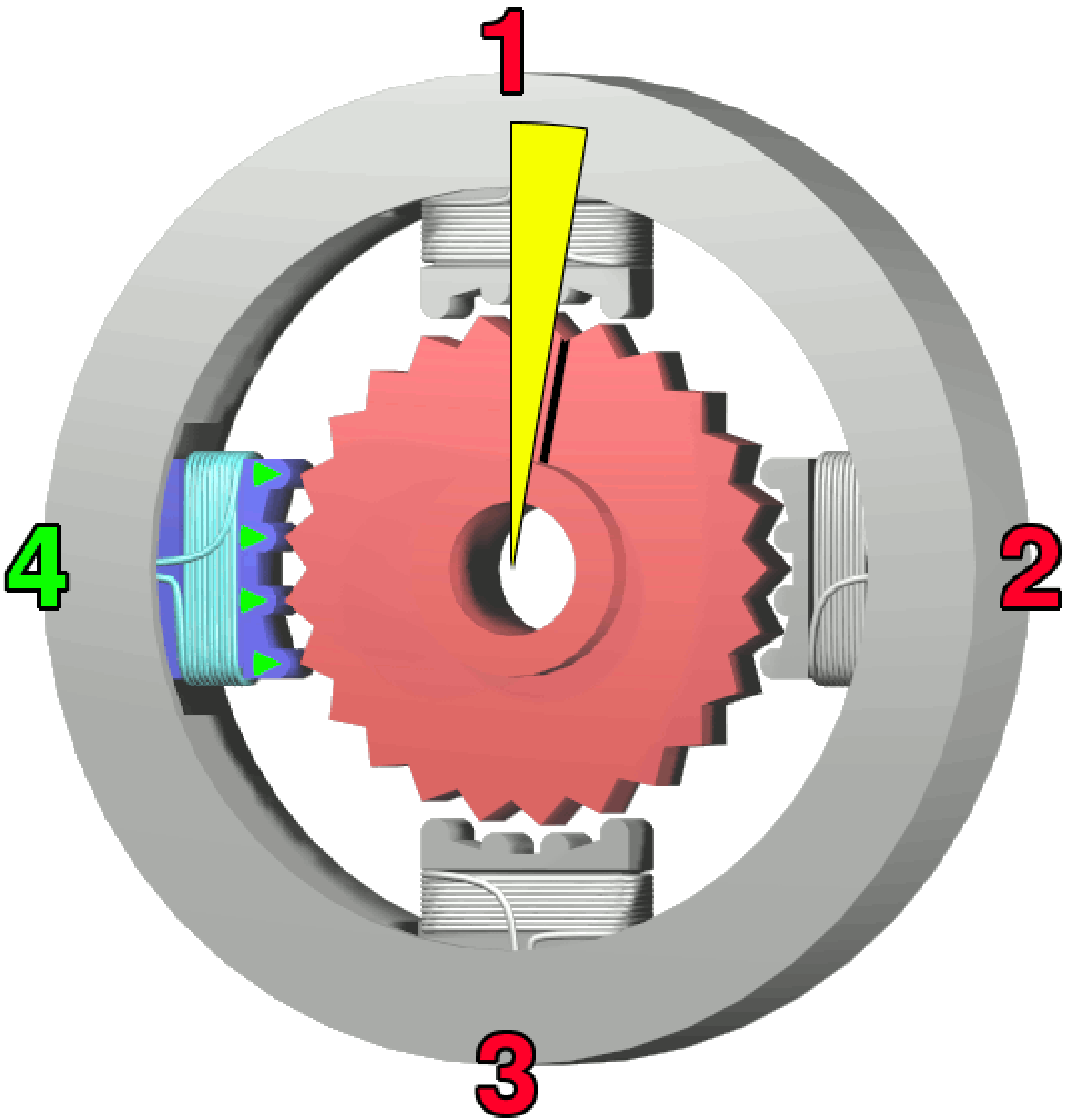


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# Stepper Motor Selection

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- Permanent Magnet / Variable Reluctance
- Unipolar vs. Bipolar
- Number of Stacks
- Number of Phases
- Degrees Per Step
- Microstepping
- Pull-In/Pull-Out Torque
- Detent Torque

# Brushless DC electric motor

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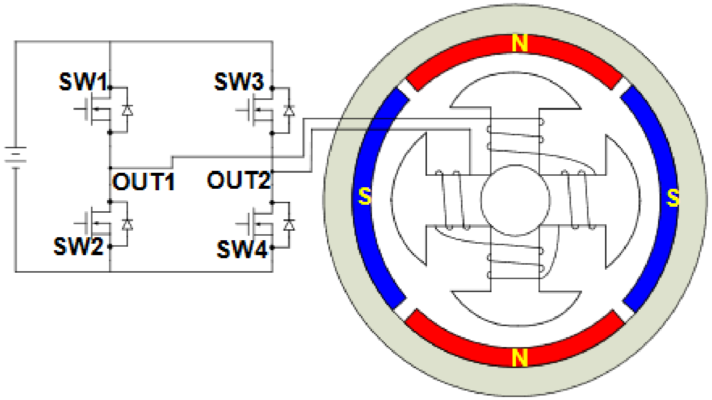
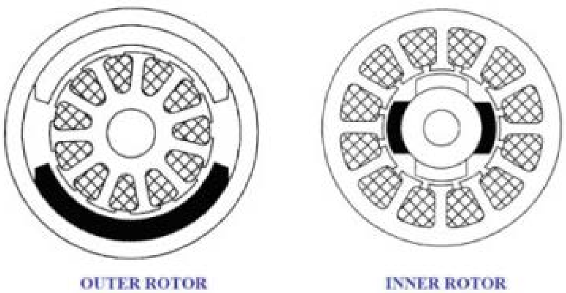
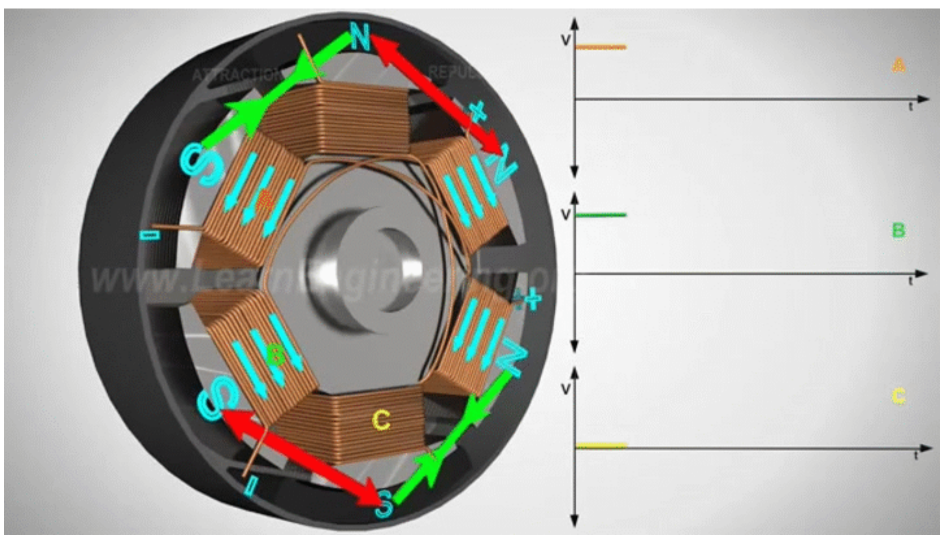
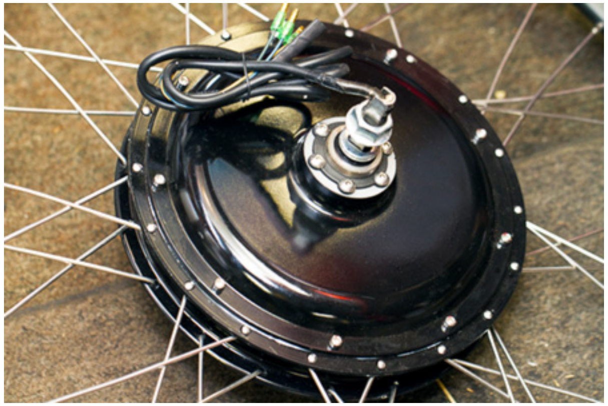
- A brushless DC motor (BLDC) is a permanent magnet synchronous electric motor.
- Position and speed sensor , usually Hall-effect sensor, needed for electronic control.
- Video explaining the principle.



Electric bike motor

# Hydraulic actuators

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- Linear movement.
- Big forces without gears.
- Actuators are simple.
- Used often in mobile machines.
- Bad efficiency.
- Motor, pump, actuator combination is lighter than motor, generator, battery, motor & gear combination.

# Hydraulic actuators, examples

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# Hydraulic pump (1)

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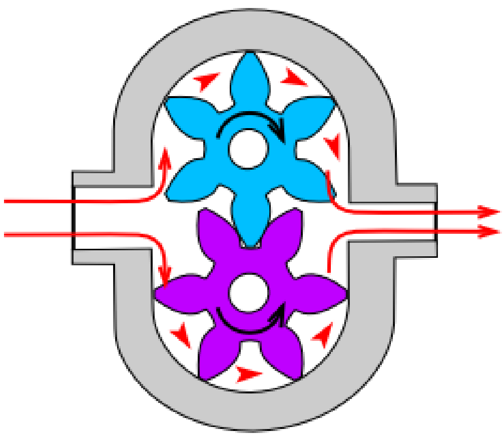
- Gear pump

  Lowest efficiency ~ 90 %

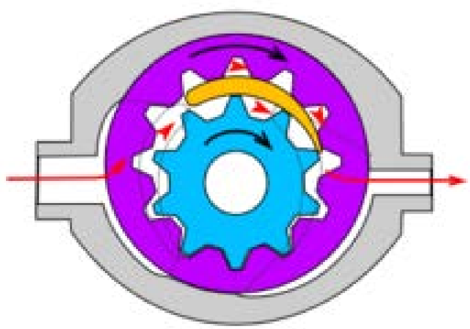
- Rotary vane pump

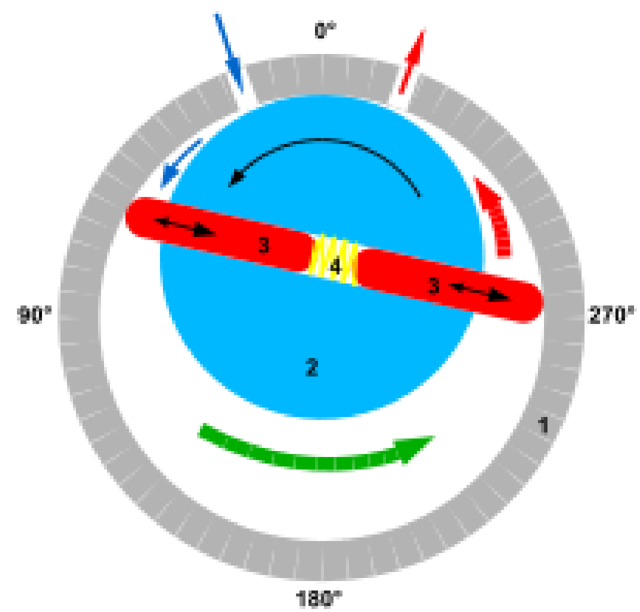
  Mid-pressure ~ 180 bars

External teeth



Internal teeth





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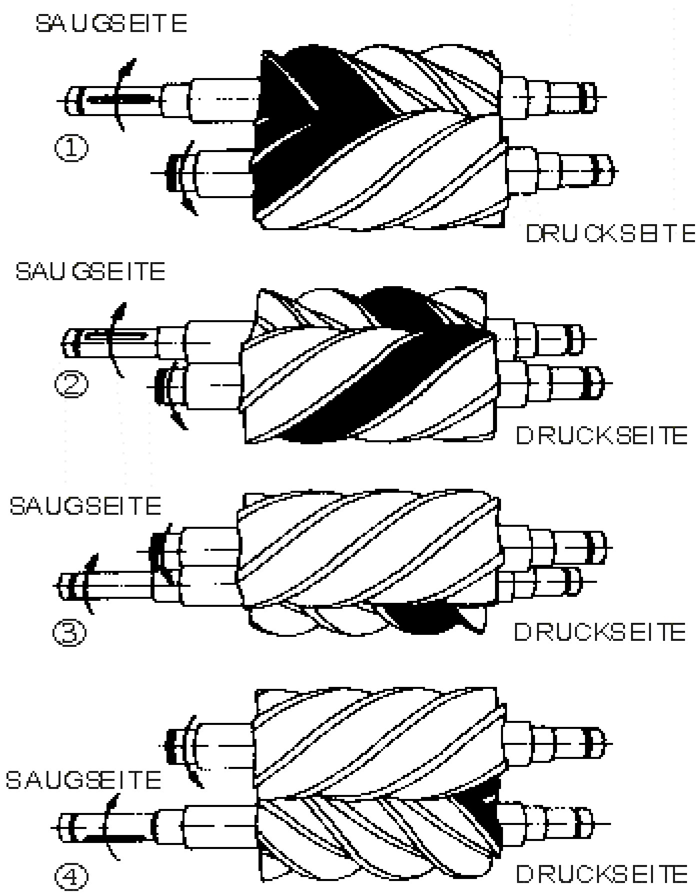
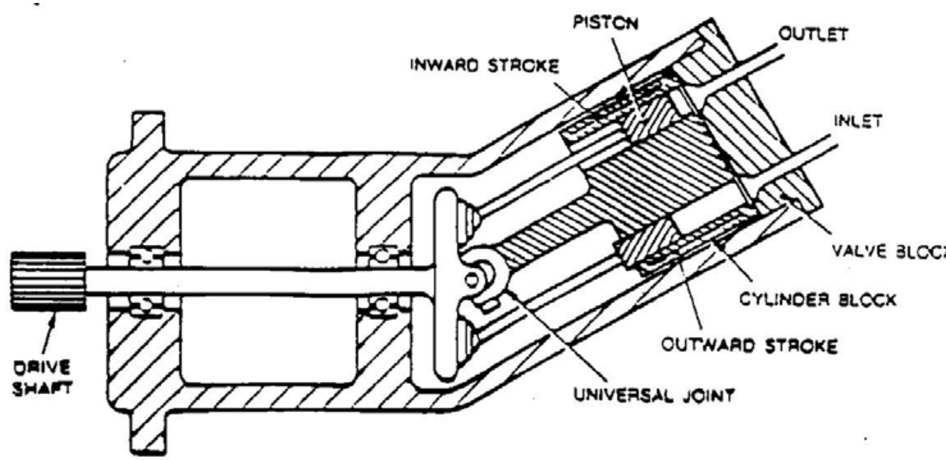
- Archimedes screw pump



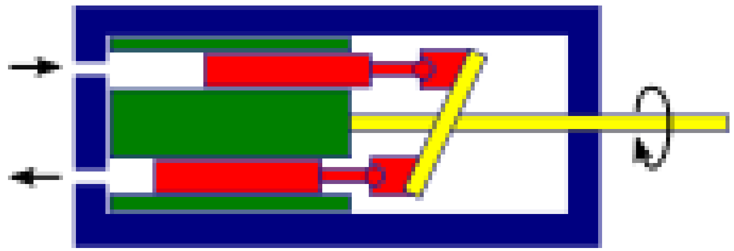

- Bent axis pump



# Hydraulic pump (3)

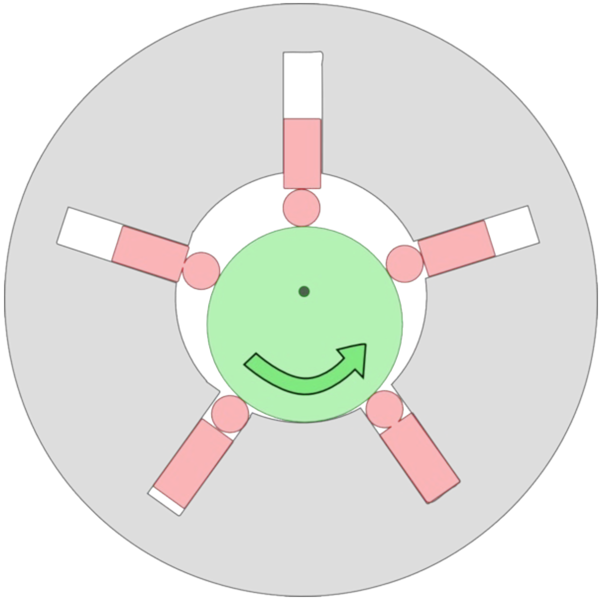


- Axial piston pumps, swashplate principle

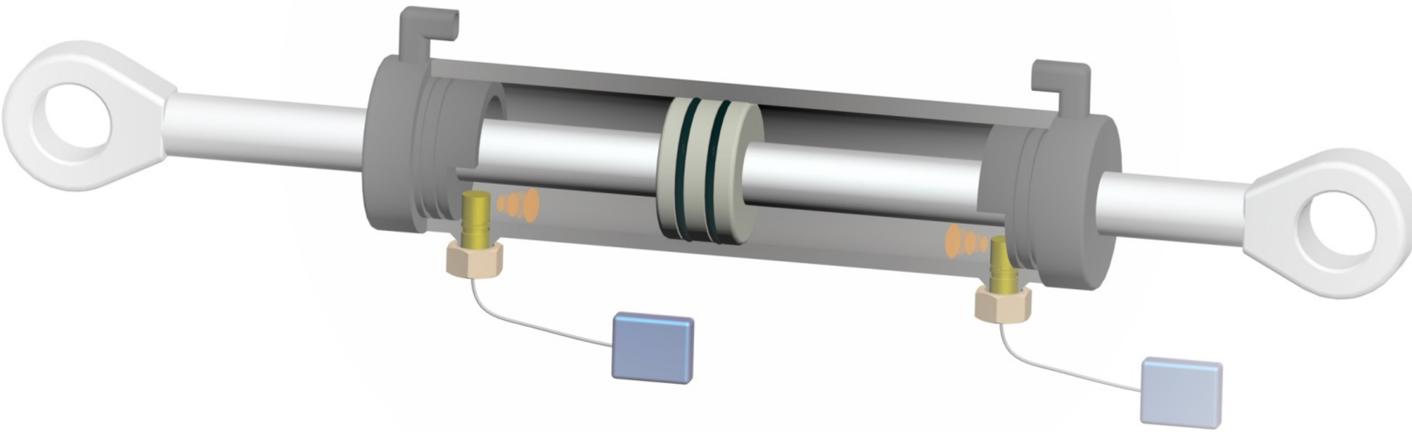


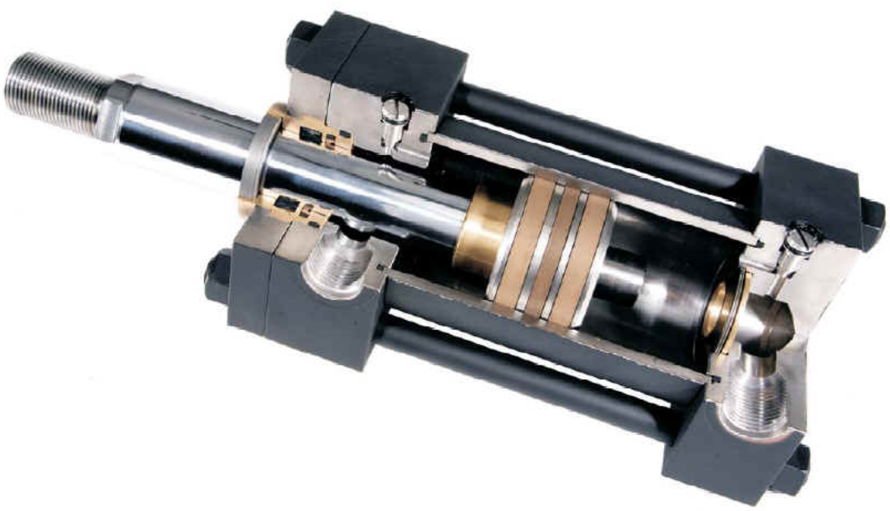
- Radial piston pump

  High pressure (~ 650 bar)
  Small flows.



# Hydraulic cylinder





# Vane motor

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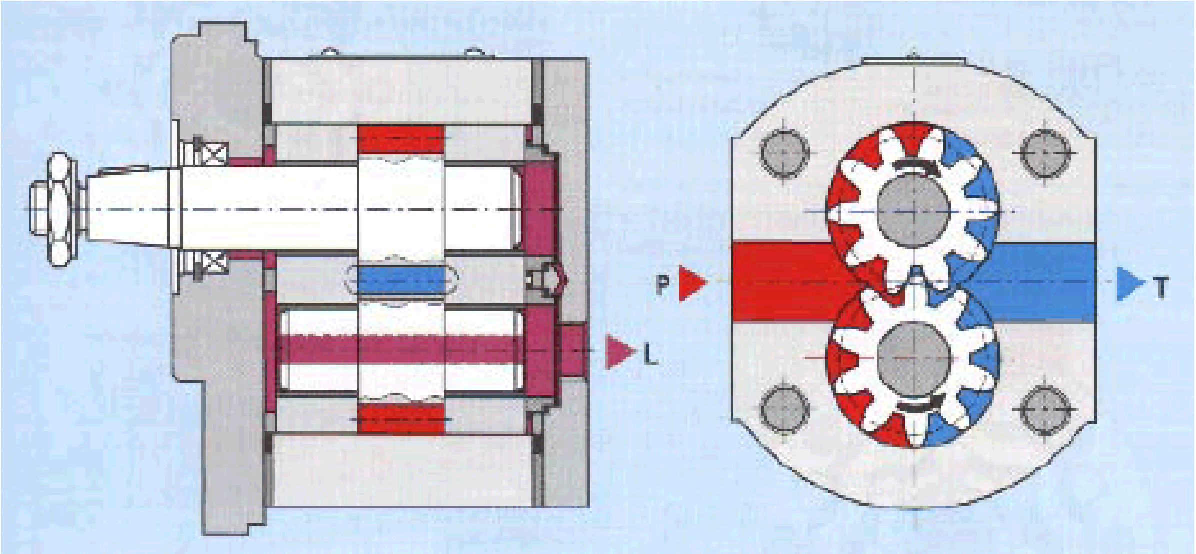
# Gear motor





# Semi-rotary piston motor

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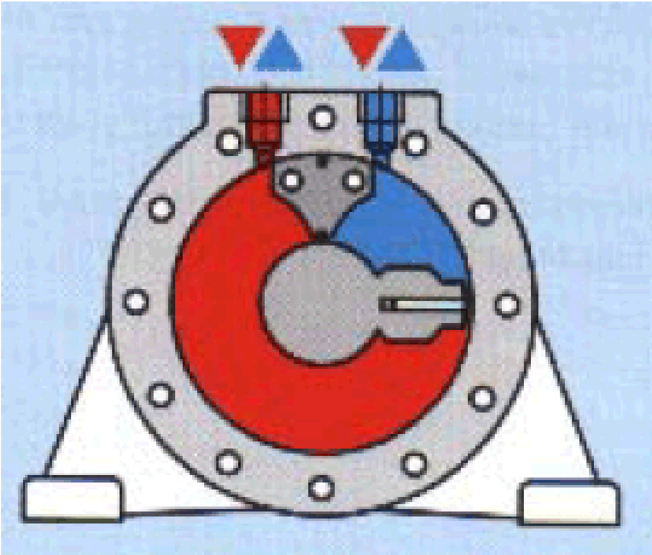
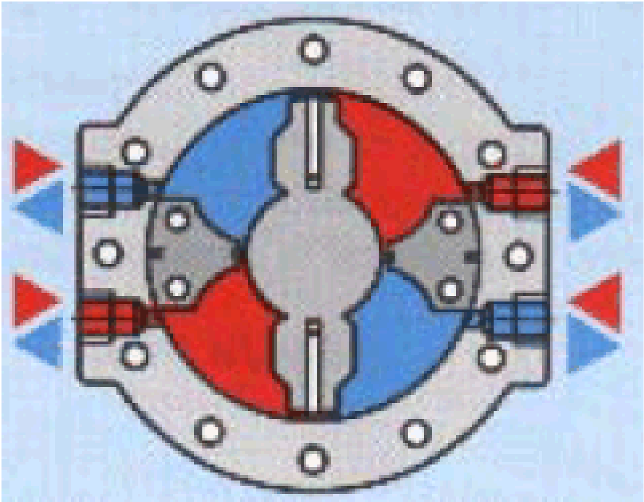
300 degrees

Large torque at low speed.



180 degrees

Doubles the torque.



# Radial piston motor

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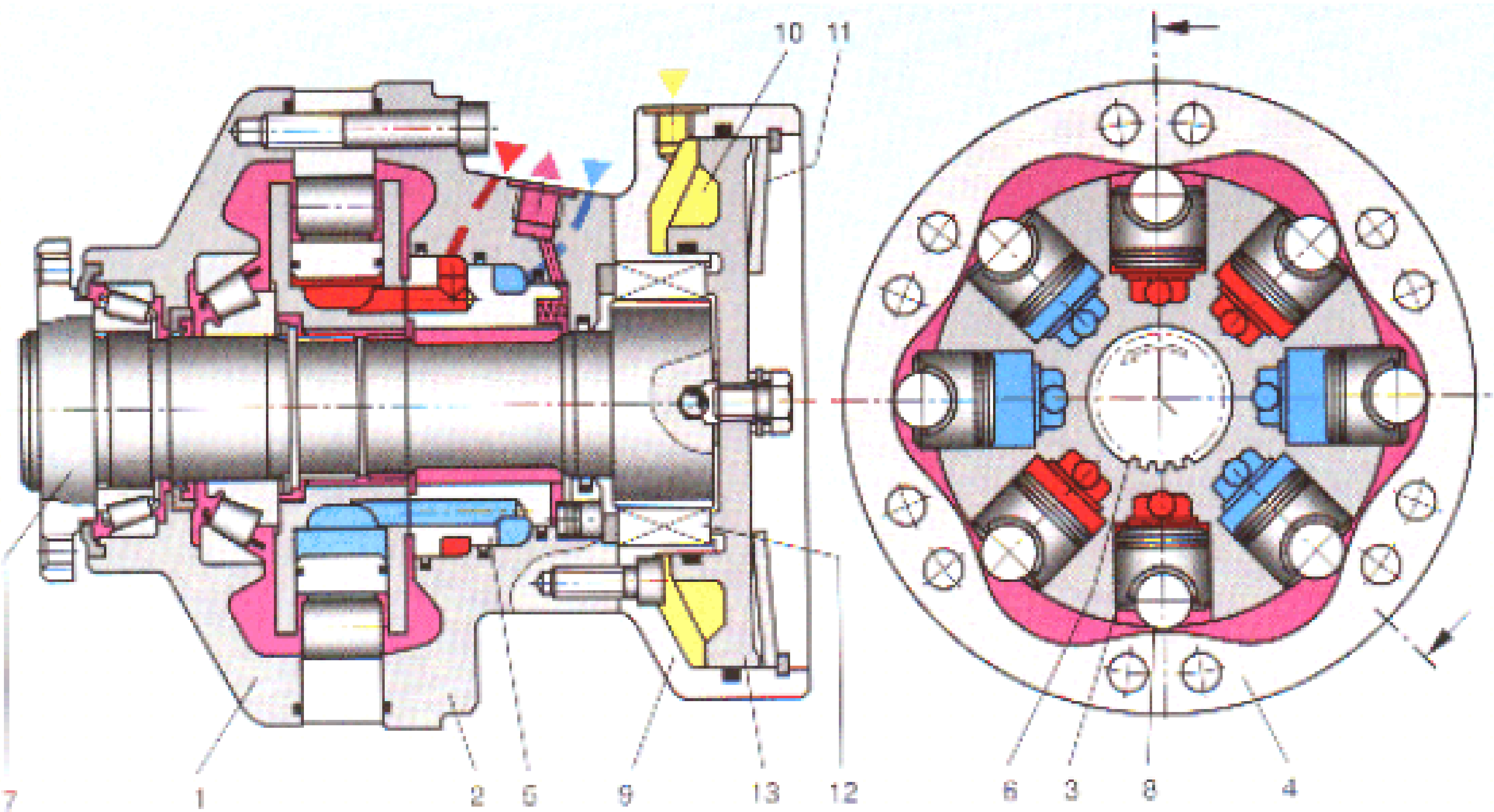
High starting torque



# Real hydraulic motor

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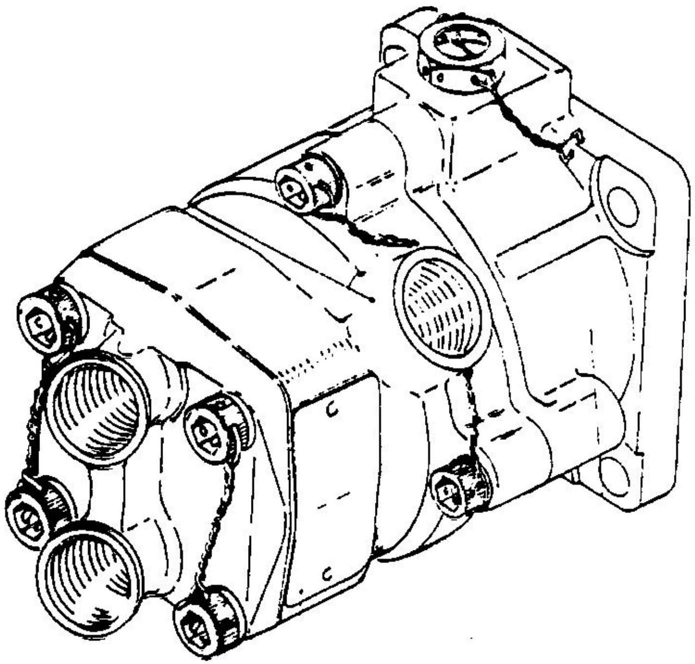

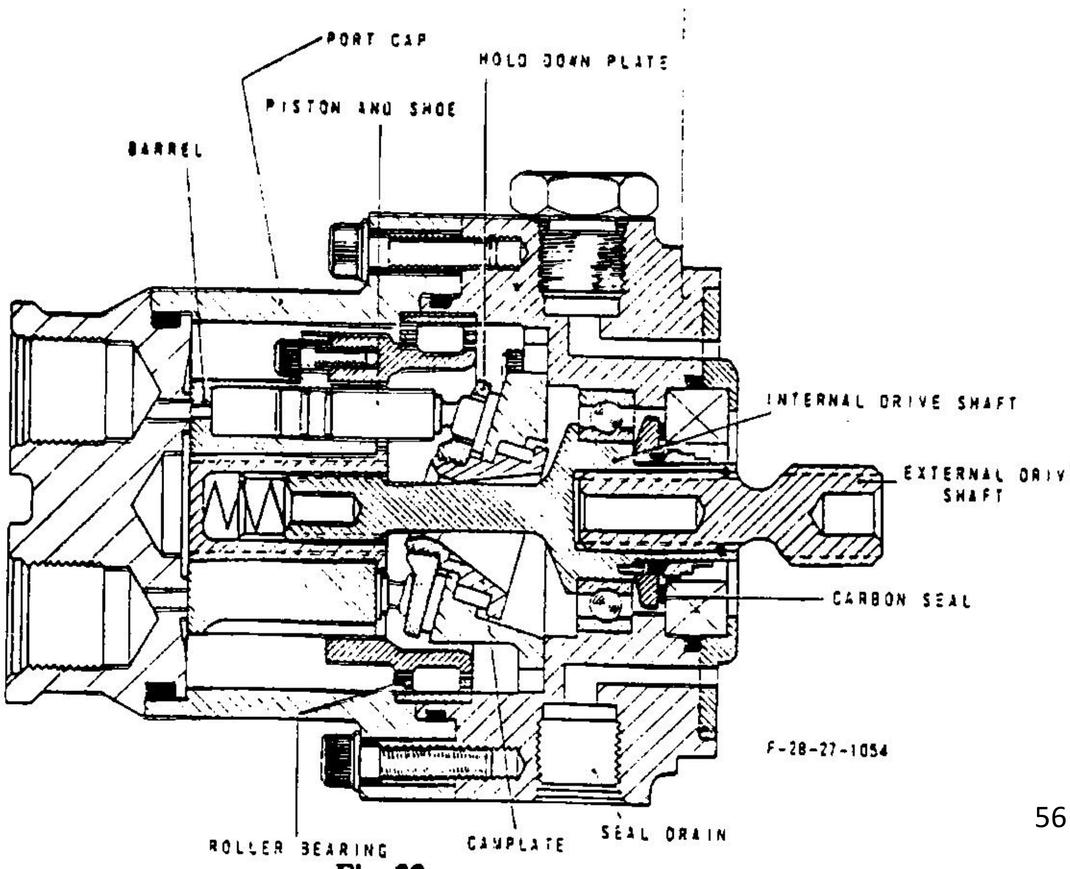

# Pneumatic actuators

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- Like hydraulic except power from compressed air.
- Advantages:
  - Fast on/off type tasks.
  - Big forces with elasticity.
  - No hydraulic oil leak problems.
- Disadvantage:
  - Speed control is not possible because the air pressure depends on many variables that are out of control.

# Other Actuators



- Piezoelectric.
- Magnetic.
- Ultrasound.
- Shape Memory Alloys (SMA).
- Inertial.

# Examples

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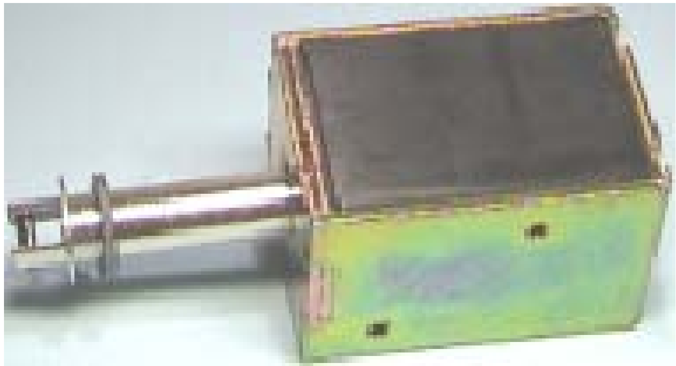

# Muscles

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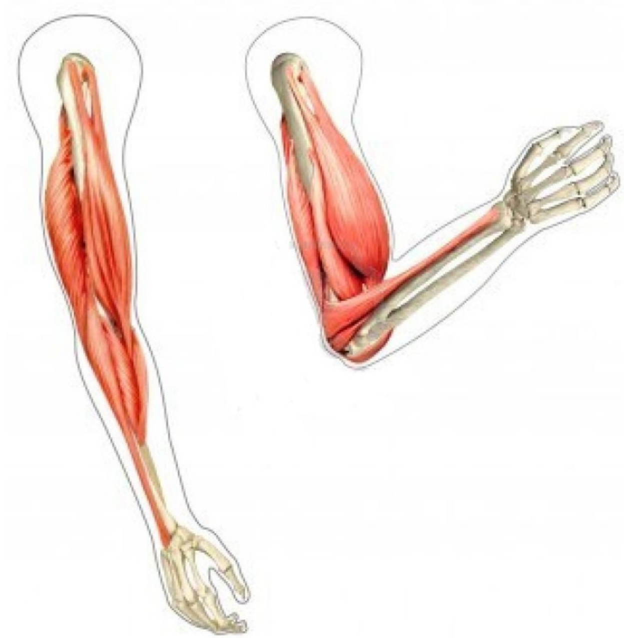
- Muscles contract when activated.
- Muscles are also attached to bones on two sides of a joint. The longitudinal  shortening produces joint rotation.
- Bilateral motion requires pairs of muscles attached on opposite sides of a joint are required.



# Muscles inside

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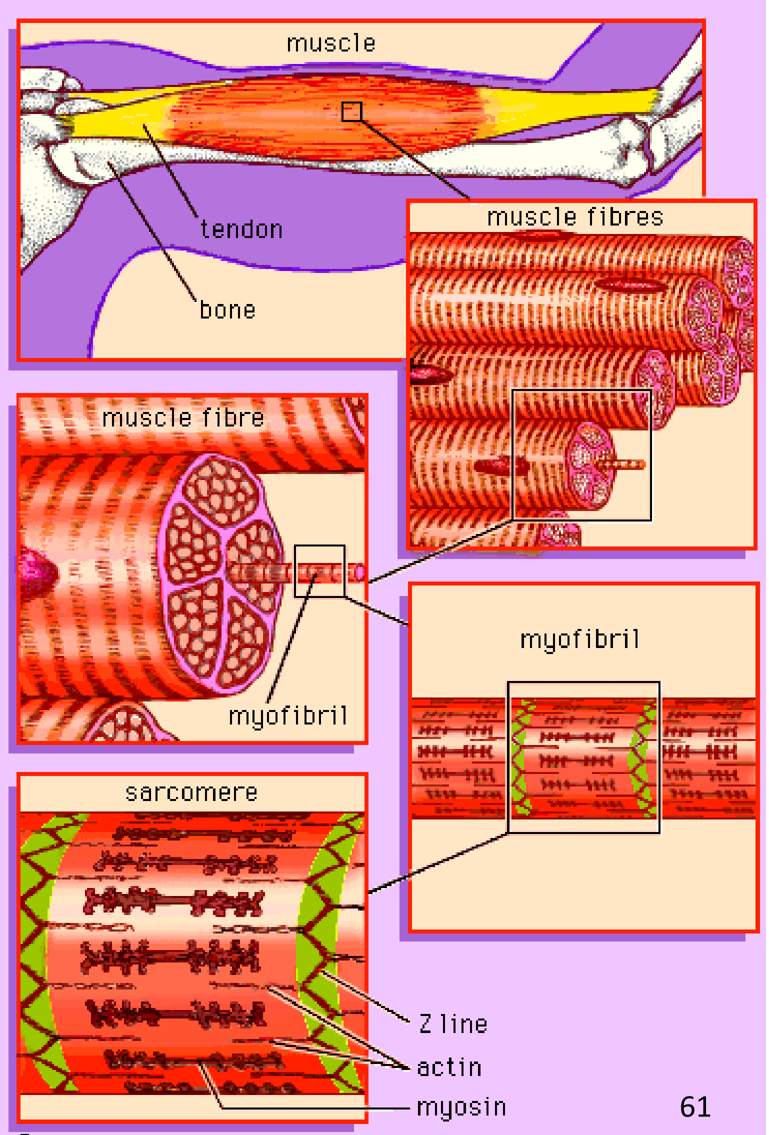
- Muscles consist of long slender cells (fibres), each of which is a bundle of finer fibrils.
- Within each fibril are relatively thick filaments of the protein myosin and thin ones of actin and other proteins.
- Tension in active muscles is produced by cross bridges



# Artificial muscles, properties

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- Mechanical properties: elastic modulus, tensile strength, stress-strain, fatigue life, thermal and electrical conductivity.
- Thermodynamic issues: efficiency, power and force density, power limits.
- Packaging: power supply/delivery, device construction, manufacturing, control, integration.

# Artificial muscles, technology 1

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1. Traditional mechatronic muscles, e.g. pneumatic.
2. Shape memory alloys, e.g. NiTi.
3. Chemical polymers - gels (Jello, vitreous humor)
   - 1000-fold volume change ~ temp, pH, electric fields. Force up to 100 $N/cm^2$.
   - 25 µm fiber → 1 Hz, 1 cm fiber → 1 cycle/2.5 days.
4. Electro active polymers
   - Store electrons in large molecules. Deformation ~ $(voltage)^2$.
   - Change length of chemical bonds.

# Artificial muscles, technology 2

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## 5. Biological Muscle Proteins

- Actin and myosin.
- 0.001 mm/sec in a petri dish.

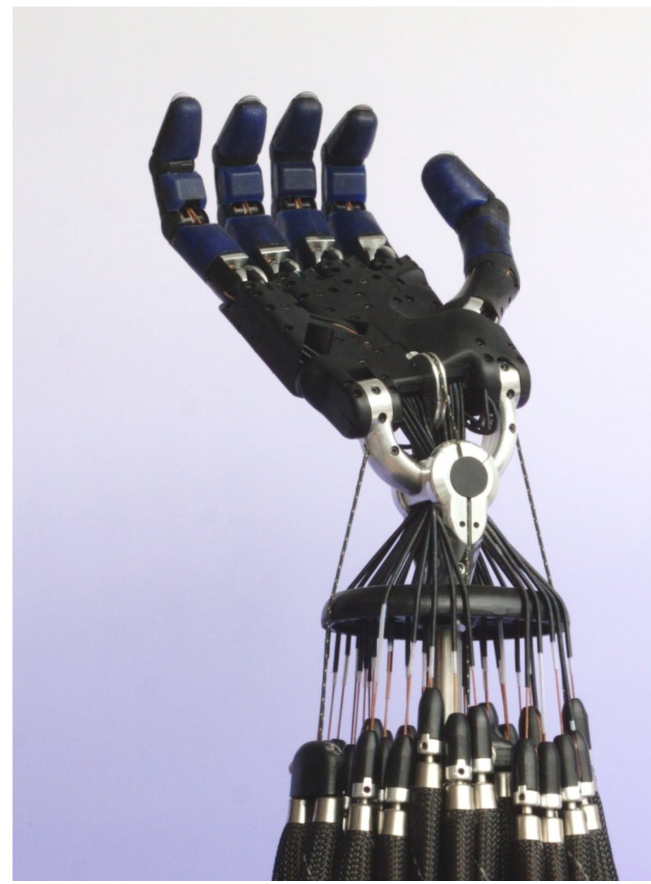
## 6. Fullerenes and Nanotubes

- Graphitic carbon.
- High elastic modulus → large displacements, large forces.
- Macro-, micro-, and nano-scale
- Potentially superior to biological muscle.

# Pneumatic artificial muscle



- Called also McKibben muscle.
- In development since 1950s.
- Contractile or extensional devices operated by pressurized air filling a pneumatic bladder.
- Very lightweight, based on a thin membrane.
- Current top implementation: Shadow hand.



# Artificial Muscles: McKibben Type

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- (Brooks, 1977) developed an artificial muscle for control of the arms of the humanoid torso Cog.
- (Pratt and Williamson 1995) developed artificial muscles for control of leg movements in a biped walking robot.

# Shape memory alloys 1

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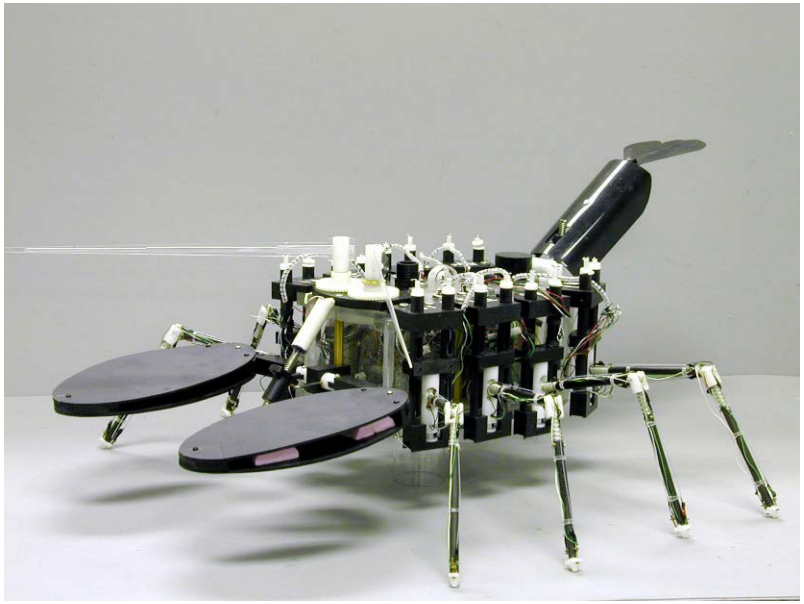
- Nickel Titanium – *Nitinol.*
- Crystalographic phase transformation from Martesite to Austenite.
- Contract 5-7% of length when heated - 100 times greater effect than thermal expansion.
- Relatively high forces.
- About 1 Hz.
- Structural fatigue – a failure mode caused by which cyclic loading which results in catastrophic fraction.

# Robot Lobster, an example



- A robot lobster developed at Northeastern University used SMAs very cleverly
- The force levels required for the lobster's legs are not excessive for SMAs
- Because the robot is used underwater cooling is supplied naturally by seawater



More on the robot lobster is available at: http://www.neurotechnology.neu.edu

# Artificial Muscles: Electroactive Polymers



- Like SMAs, Electroactive Polymers (EAPs) also hange their shape when electrically stimulated
- The advantages of EAPs for robotics are that they are able to emulate biological muscles with a high degree of toughness, large actuation strain, and inherent vibration damping
- Unfortunately, the force actuation and mechanical energy density of EAPs are relatively low

# Electroactive Polymer Example

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Robotic face developed by a group led by David Hanson. More information is available at: www.hansonrobotics.com