Cyber-Physical Systems

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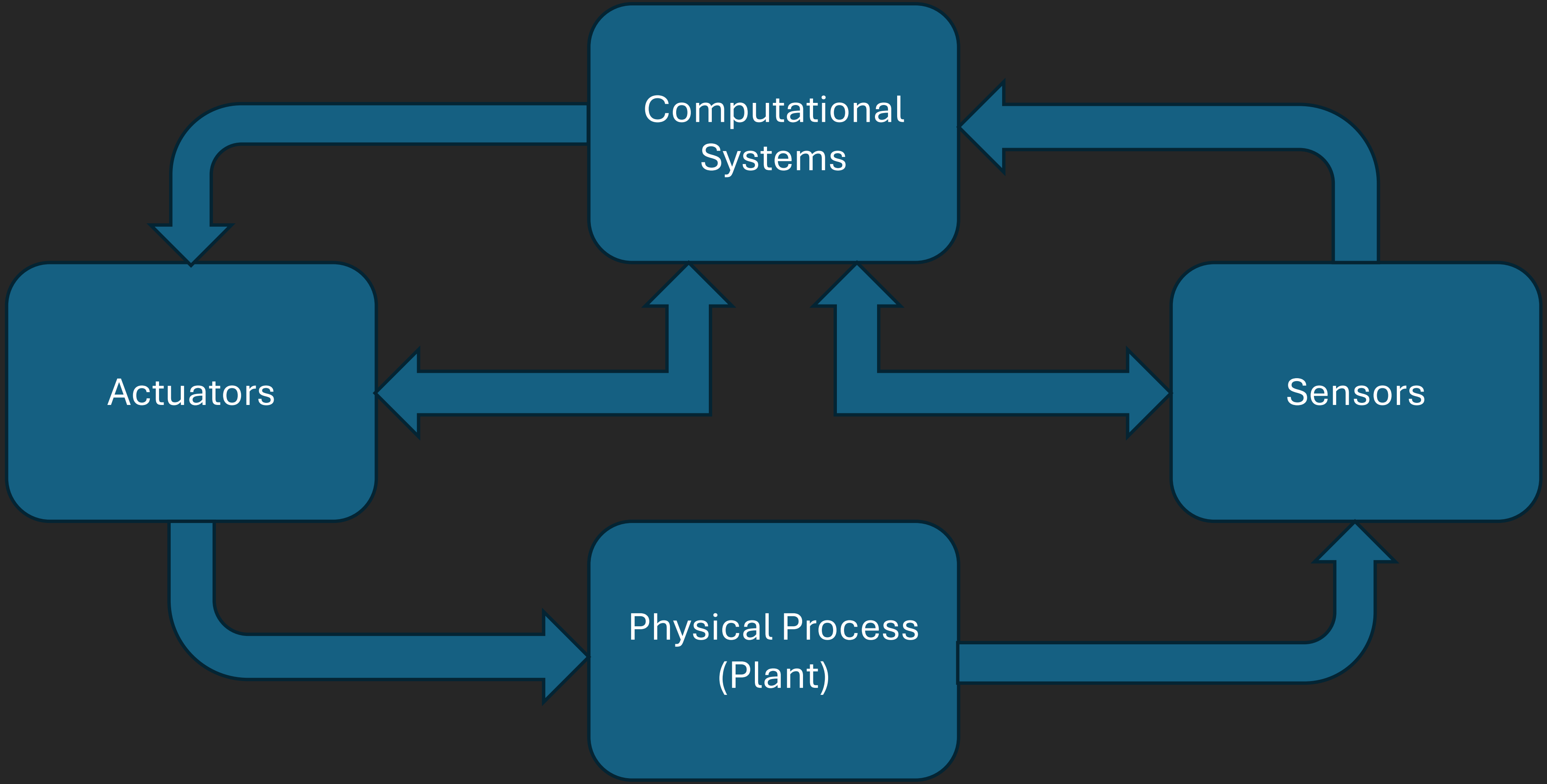
Actuators

Actuators

- An actuators is physical devices that convert electrical, hydraulic, or pneumatic energy into mechanical motion
- They serve as the output components of a CPS, allowing digital control systems to interact with the physical world
- Examples include motors, hydraulic pistons, solenoids, and piezoelectric element

What are Cyber-Physical Systems?



Digital to Analog Converter (DAC)

- An electronic device that converts digital signals (binary data) into analog signals (continuous voltages or currents)
- Why do we need DACs?
  - Most actuators require an analog input signal to function

Key Characteristics of DACs

- Resolution: The number of discrete levels the DAC can produce
  - Higher resolution results in higher precision
- Update Rate: Speed at which DAC updates its value
  - Determines maximum frequency produced by DAC
- Reference Voltage: Maximum voltage produced by DAC
  - Can be internal or external reference
- Settling Time: The time required for the DAC to reach its final value
  - Determines maximum frequency produced by DAV

Key Characteristics of DACs

- Output Range: the voltage and current range of the DAC
  - Unipolar or Bipolar
- Linearity: how closely the DAC follows a straight line
- Noise to signal ratio
- Power consumption
- Output drive capability
- Glitch energy: small voltage spikes when changing values
- Latency: delay between digital signal and analog signal

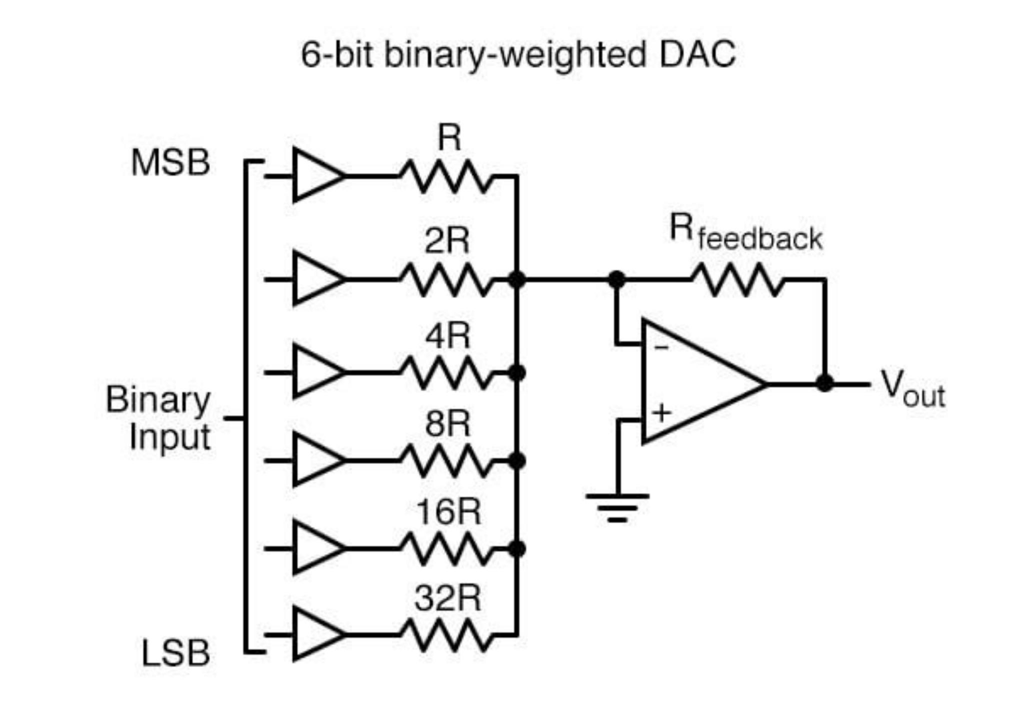
Types of DACs

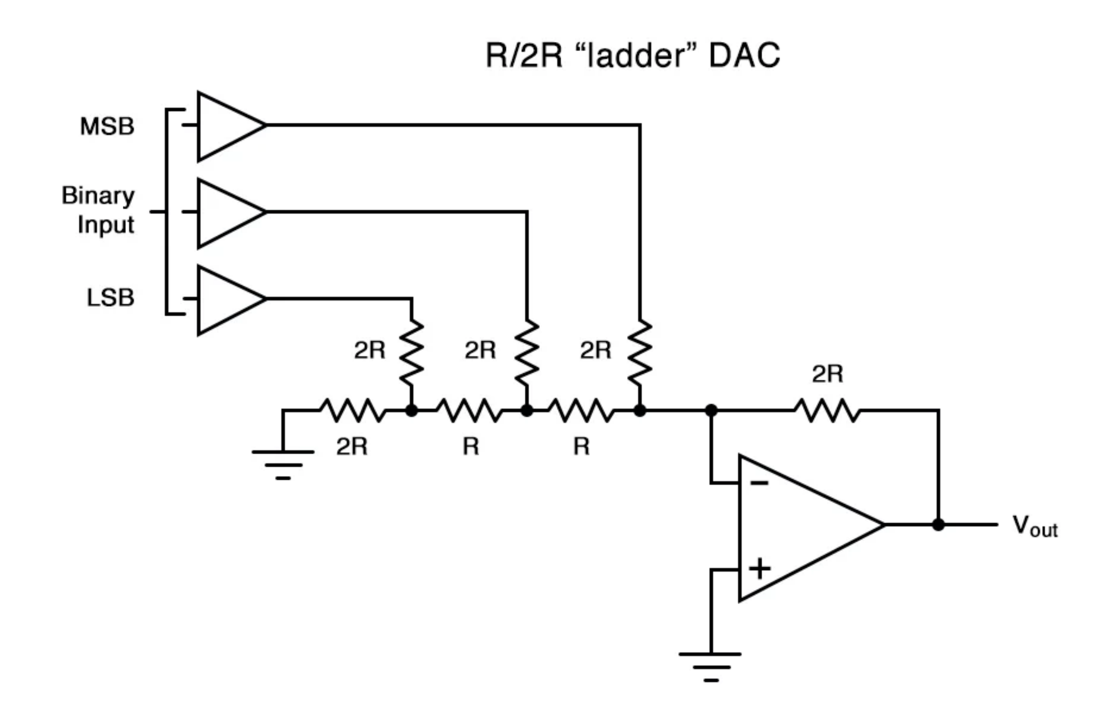
- Resistor Ladder
- Sigma-delta
- Current Steering
- Pulse Width Modulation

Resistor Ladder

- Uses a resistor network
  - Binary-Weighted DAC – resistor values follow powers of two
  - R-2R Ladder DAC – uses only two resistor values
- Operation:
  - Digital input controls switches connected to a resistor network
  - Voltage division produces an analog output proportional to the binary input
- $V_{out} = V_{ref} \times \left(\frac{D}{2^N}\right)$

Resistor Ladder





Resistor Ladder

- Advantages:
  - Simple design with fast conversion time
  - Low power consumption
  - Cost-effective and widely used
- Disadvantages:
  - Limited resolution (practical up to 12-16 bits)
  - Resistor matching errors can affect accuracy
  - Slow speed compared to other DACs

Resistor Ladder

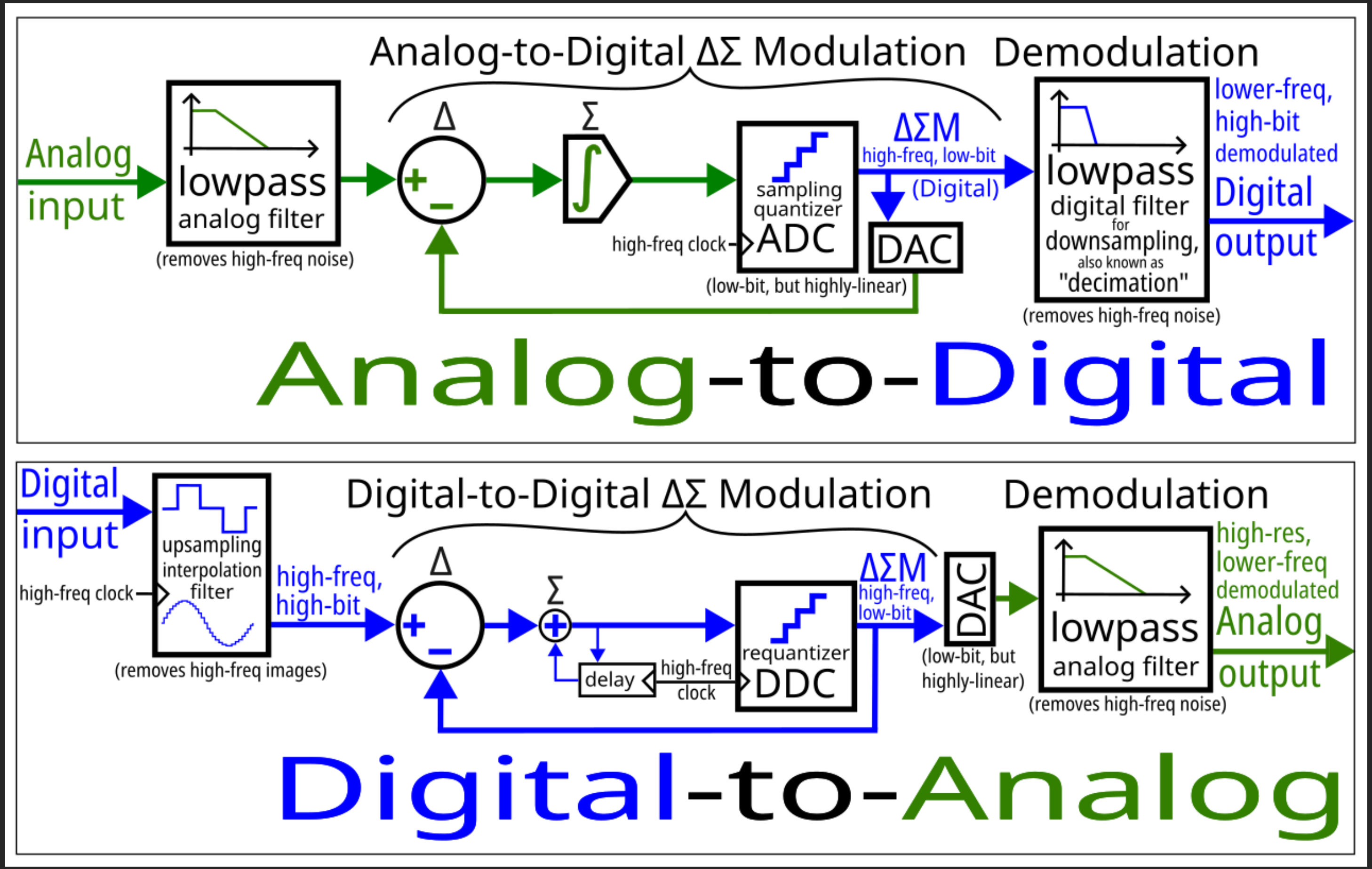
- Motor control systems (speed & torque regulation)
- Low-cost audio DACs (basic sound synthesis)
- Embedded systems (analog signal output from microcontrollers)
- Industrial instrumentation (calibrated voltage generation)

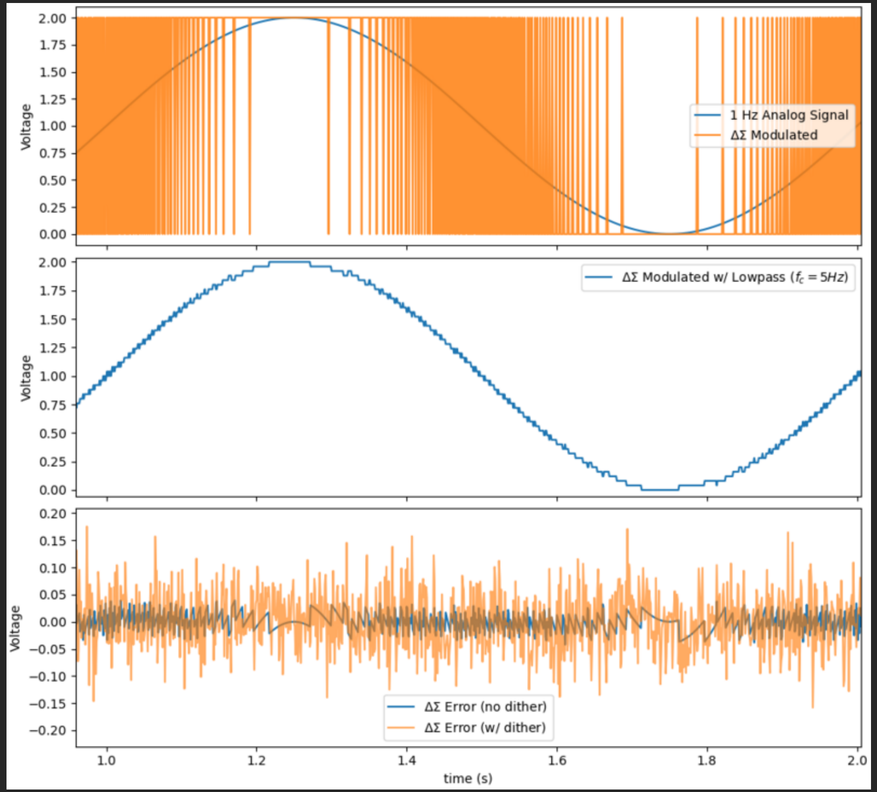
- **Cost & Simplicity**

Sigma-Delta DAC

- Uses oversampling and noise shaping to produce a high-resolution output
- Operation:
  - Oversampling: Input signal is sampled at a higher rate
  - Sigma-Delta Modulation: Converts input into a 1-bit bitstream (PDM)
  - Low-Pass Filtering: Analog filter smooths the output signal

Sigma-Delta DAC





Delta-Sigma DAC

- Advantages:
  - High resolution (16-24 bits)
  - Excellent linearity and low noise
  - Efficient in low-frequency applications
- Disadvantages:
  - Slow response time due to oversampling
  - Requires digital signal processing (DSP)
  - Not ideal for real-time control applications
- Applications: high-fidelity audio systems, medical instrumentation communications systems

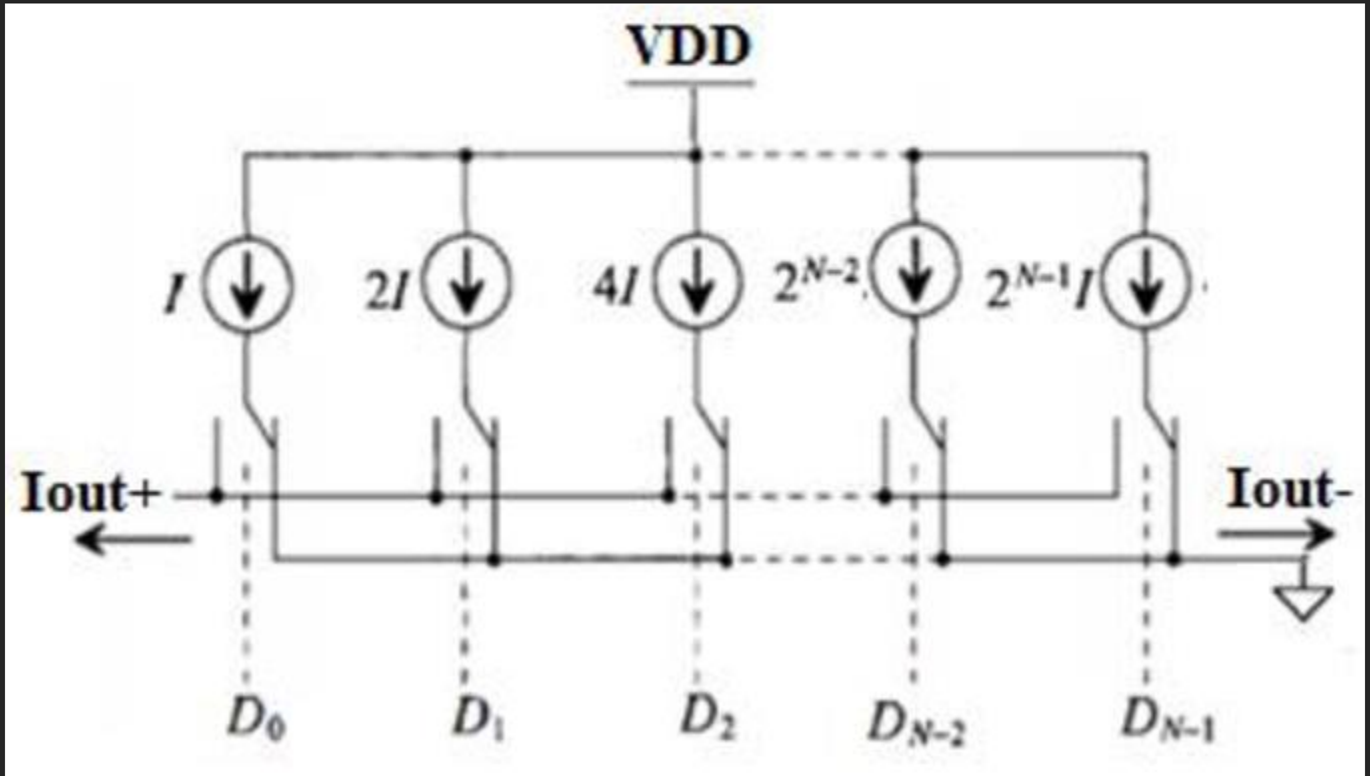
Current Steering DAC

- Uses a current sources rather than resistors
- Operation:
  - Each digital input bit controls a switch that either directs a current to the output node
  - The total output current is the sum of the currents
  - Current is converted to voltage using a resistor
- Current source: Cascode transistor
  - Create a high-impedance node
  - Prevents variations in output voltage from affecting current

Current Steering DAC

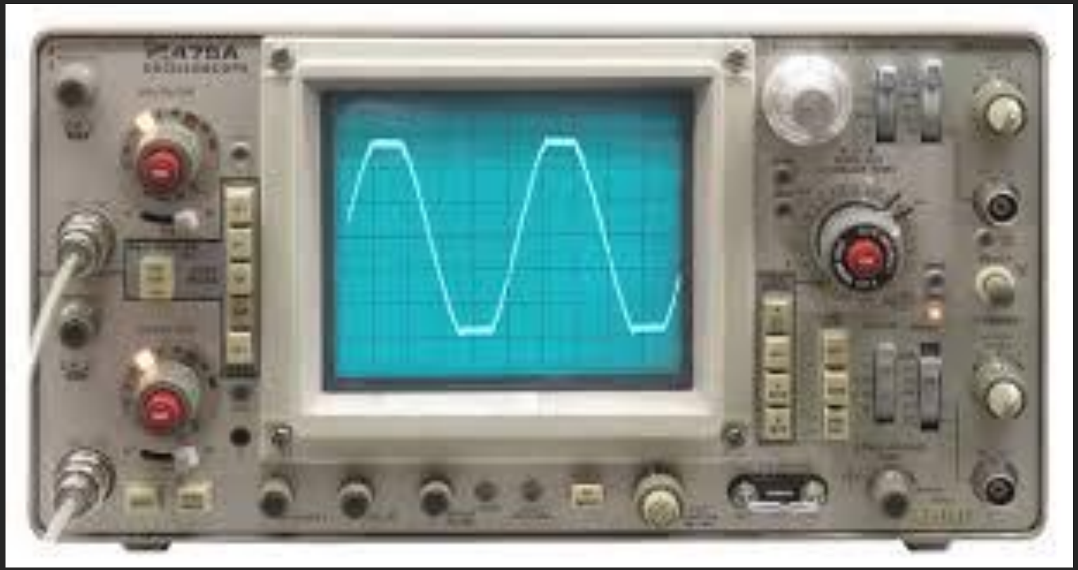
- Advantages:
  - High-speed operation (GHz range)
  - Low power consumption
  - Ideal for waveform synthesis
- Disadvantages:
  - Requires precise current matching
  - Higher power consumption at high resolutions

Current Steering DAC



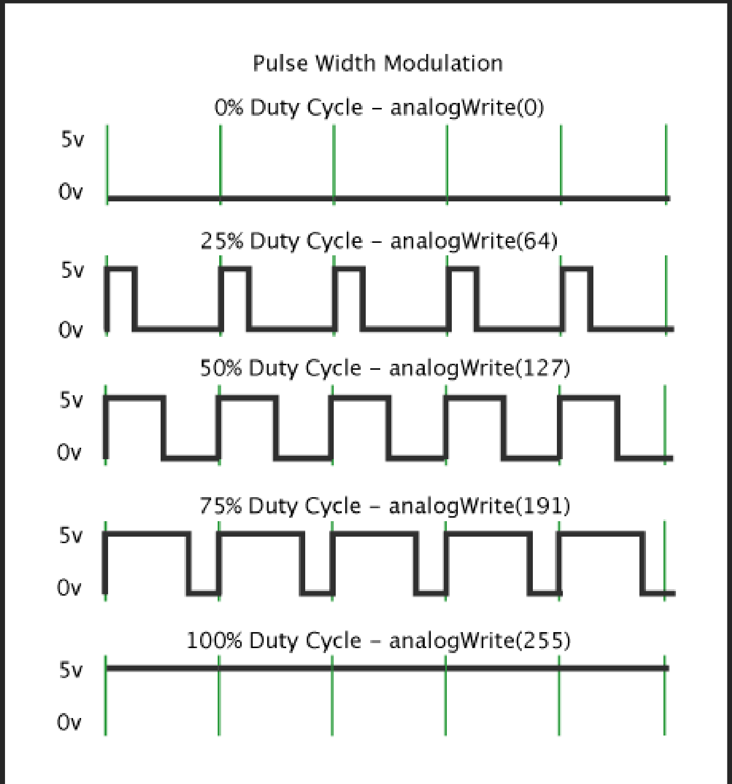
Current Steering DAC

- RF and telecommunications (modulation & transmission)
- Video processing (digital-to-analog TV conversion)
- Test & measurement equipment (oscilloscopes, analyzers)



Pulse Width Modulation (PWM) DAC

- Varies the width of a square wave to simulate analog signal
- Operation
  - The duty cycle is proportional to the digital value
  - Analog low-pass filter smooths output
- Advantages:
  - Simple and low-cost
  - Low power consumption
- Disadvantages:
  - Limited resolution
  - Requires filtering



Pulse Width Modulation (PWM) DAC

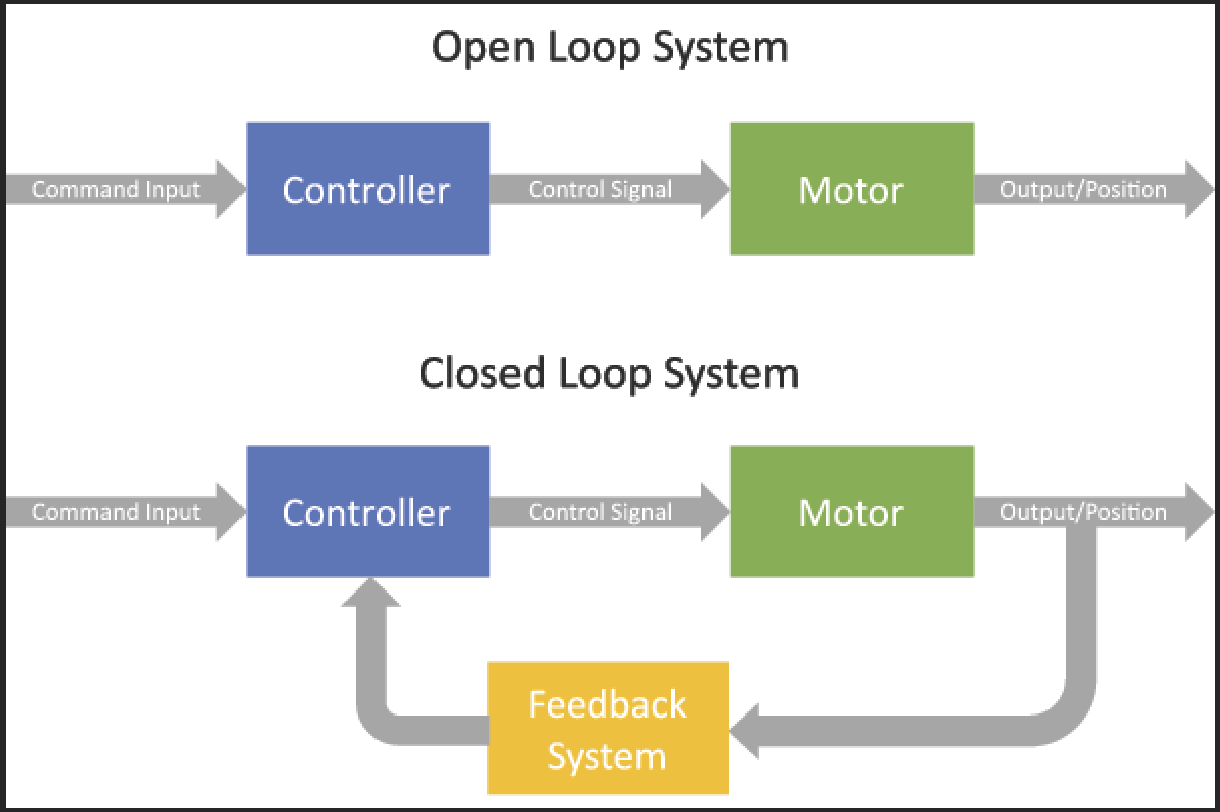
- Motor control
- LED dimming
- Power electronics

Considerations for Actuators in CPS

- Power Source
  - Electric
  - Hydraulic
  - Pneumatic
- Speed vs Force
  - Fast -> fans, speakers
  - High-force: Servos, hydraulic systems
- Precision & Range
  - Low precision: Brushed DC Motor
  - High precision: piezoelectric actuator

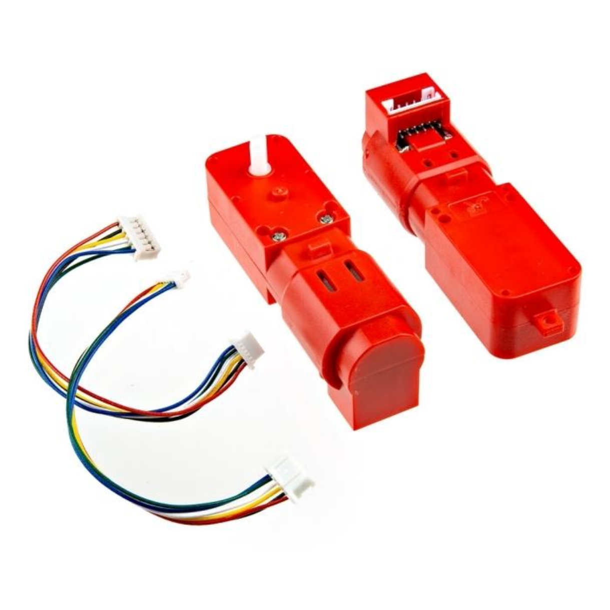
Control

- Open-Loop Control
  - No feedback, only applied control signal
  - Example: running a motor at a fixed voltage
- Closed-Loop Control
  - Uses sensor feedback to adjust control input
  - Example: servo motor with encoder



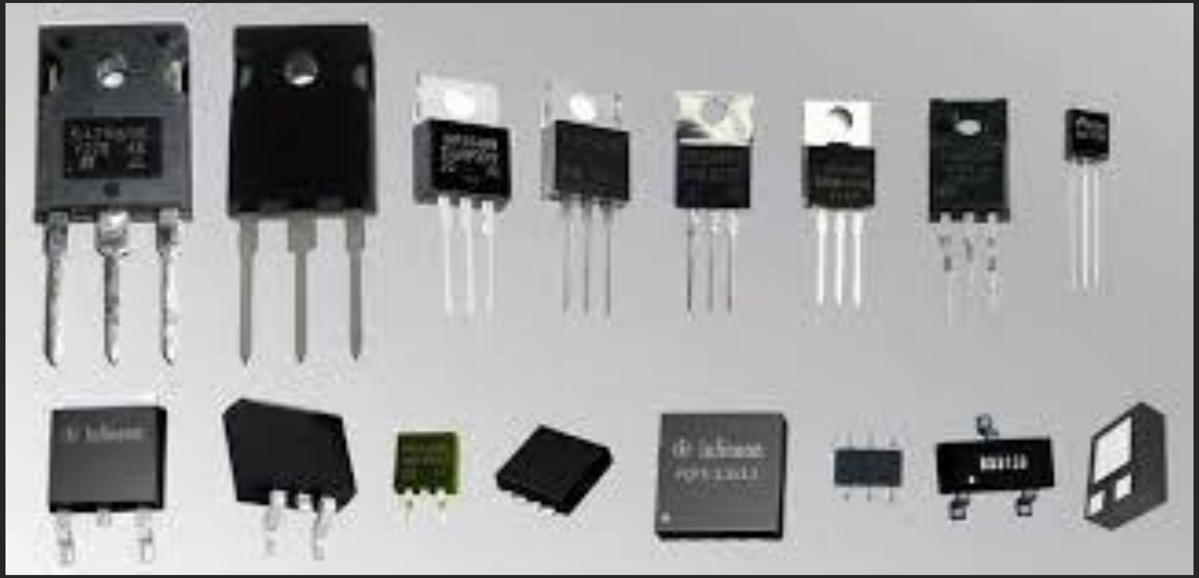
Actuator Power Electronics

- Many actuators require precise, high-power, electrical signals



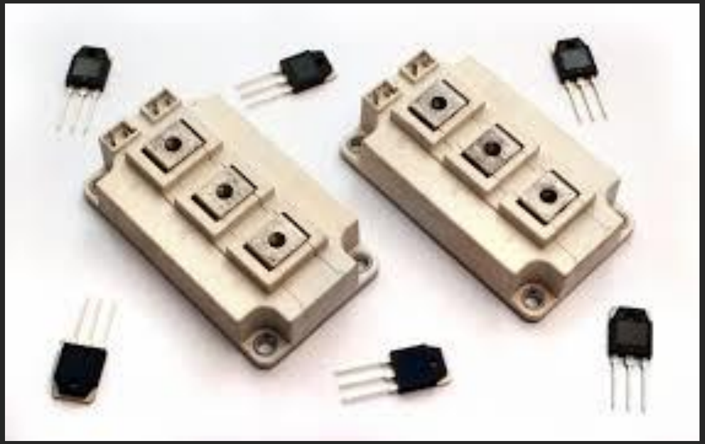
Power Switching Devices (MOSFETs)

- MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors)
  - Used for fast switching high currents with low power loss
  - Can handle high voltage (e.g., 100V+) and large currents (e.g., 50A+).
  - Used in PWM motor control, H-bridges, and power amplifiers.



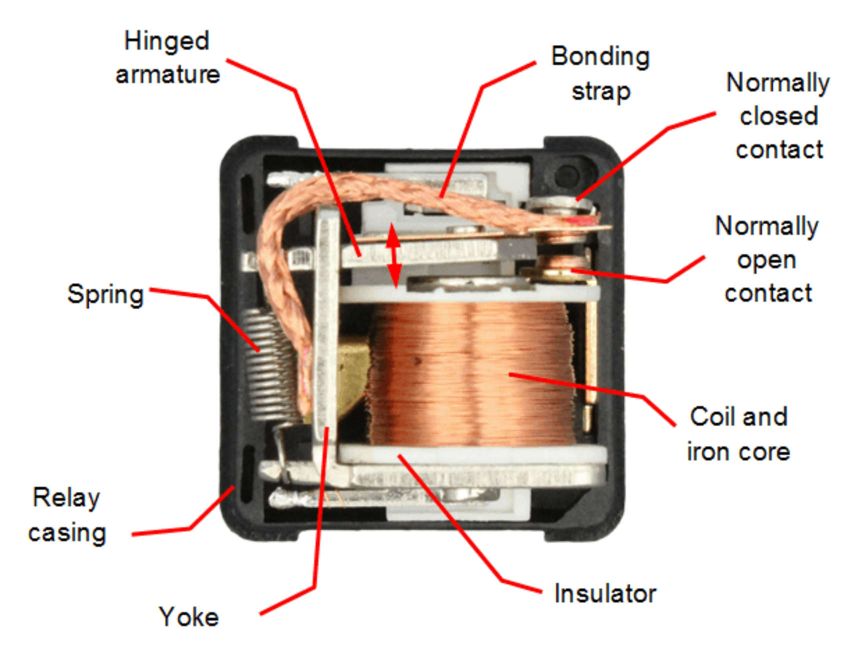
Power Switching Devices (IGBTs)

- IGBTs (Insulated Gate Bipolar Transistors)
  - Used in high-power applications (above 100V, up to kV levels)
  - Combines high current capability of BJTs with fast switching of MOSFETs
  - Common in industrial motor drives, electric vehicles, and high-voltage robotics



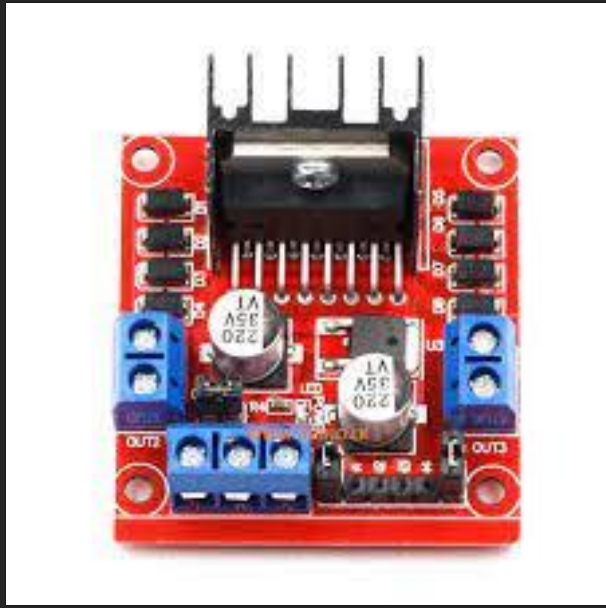
Power Switching Devices (Relays)

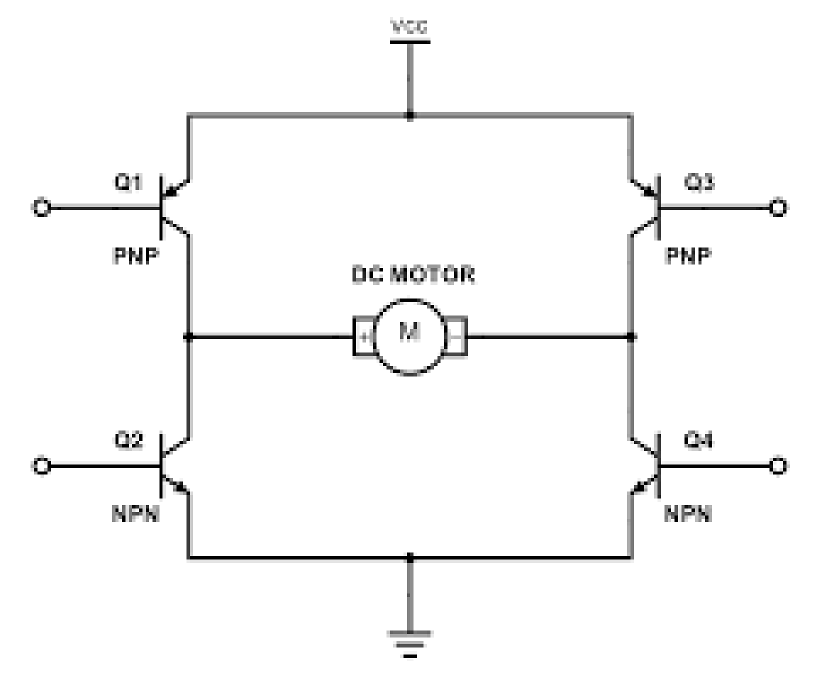
- Relay
  - Electromechanical switches for turning actuators on/off
  - Uses electromagnetic coil to move mechanical switch



Motor Driver Circuits

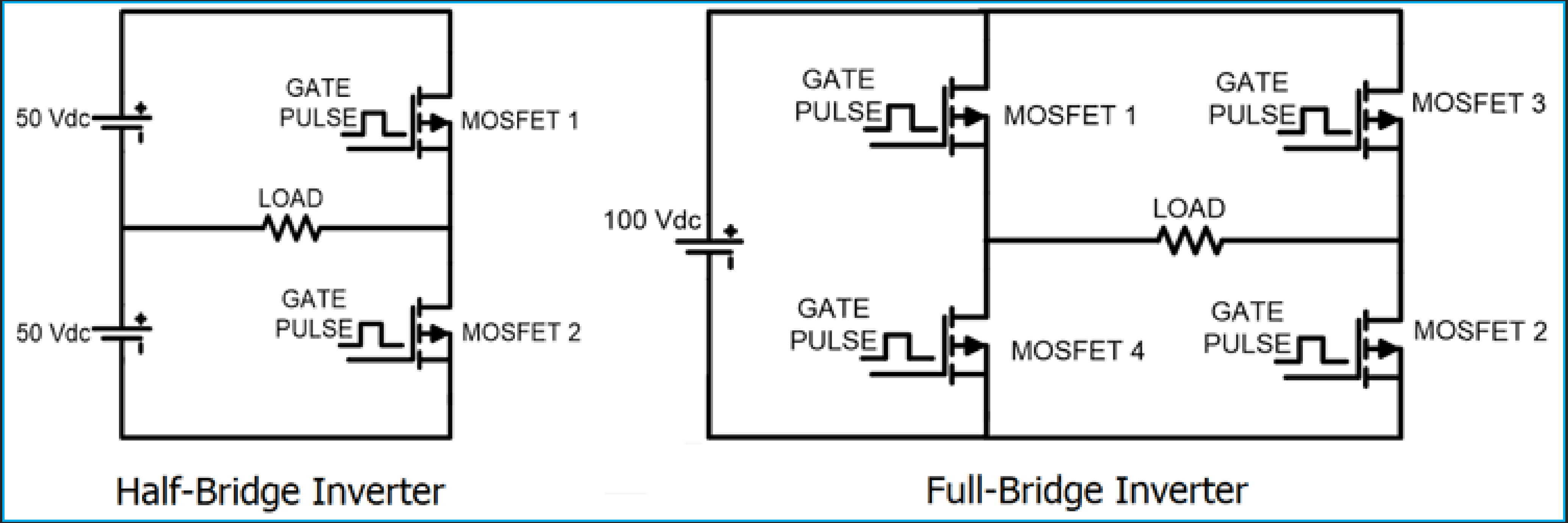
- H-Bridge
  - Consist of 4 MOSFETs or BJTs that switch in pairs
  - Allows bidirectional control (forward/reverse) of a DC motor





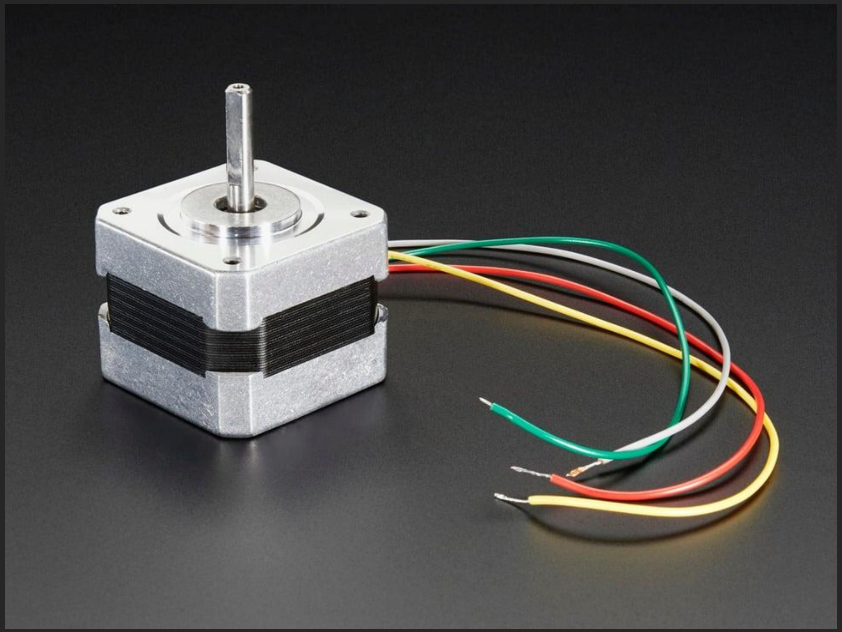
Motor Driver Circuits

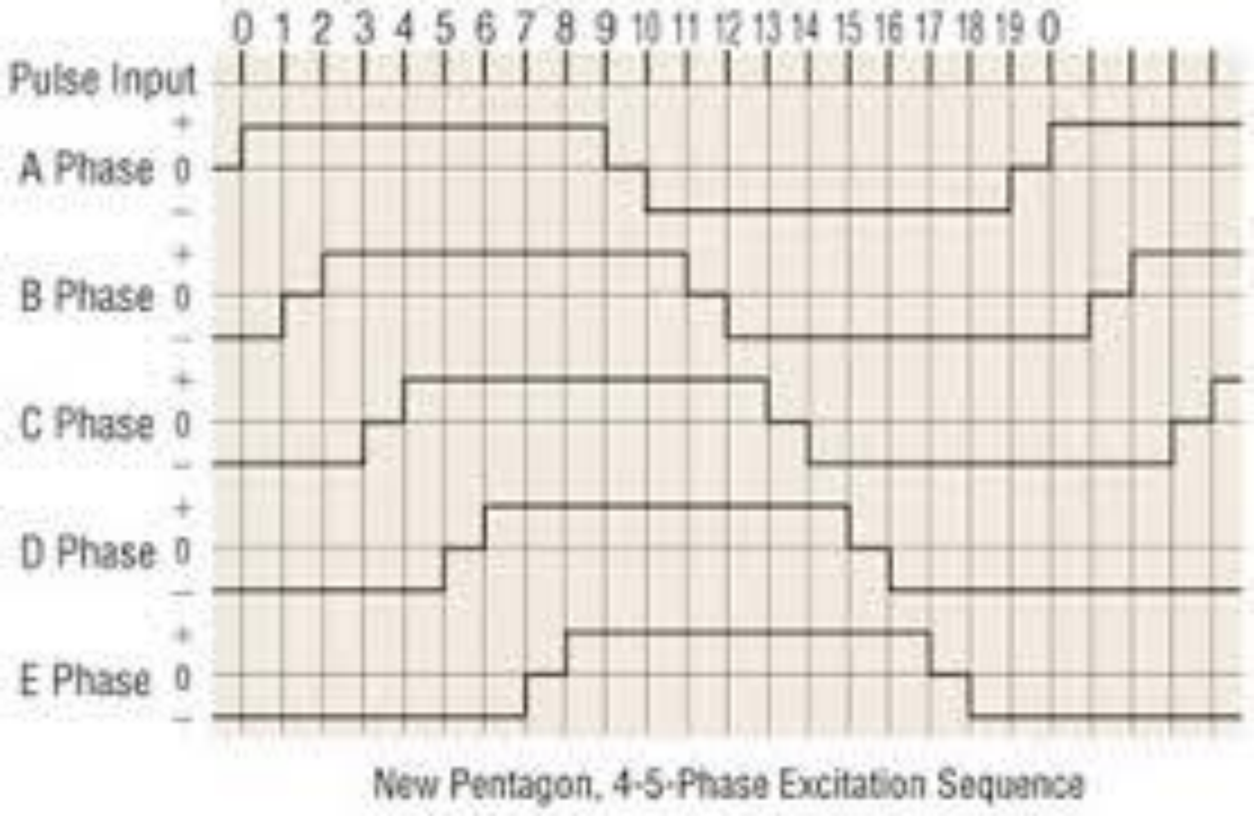
- Half Bridge



Motor Driver Circuits

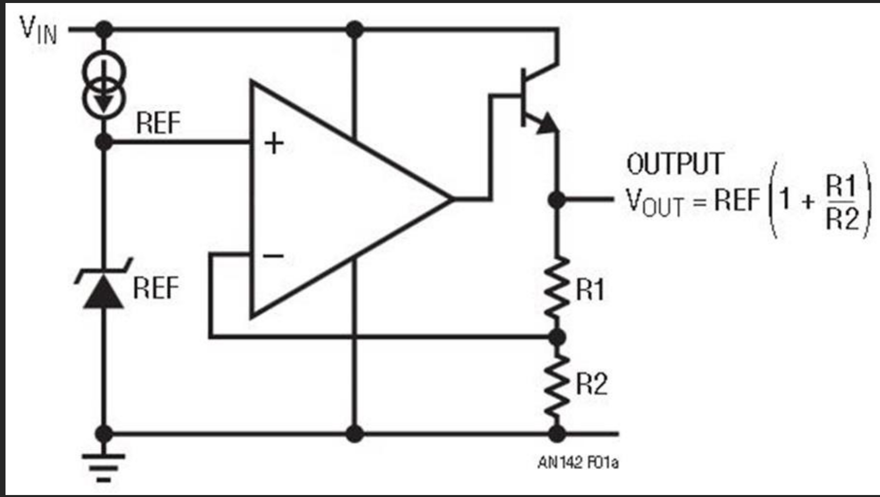
- Multi-phase motor drivers

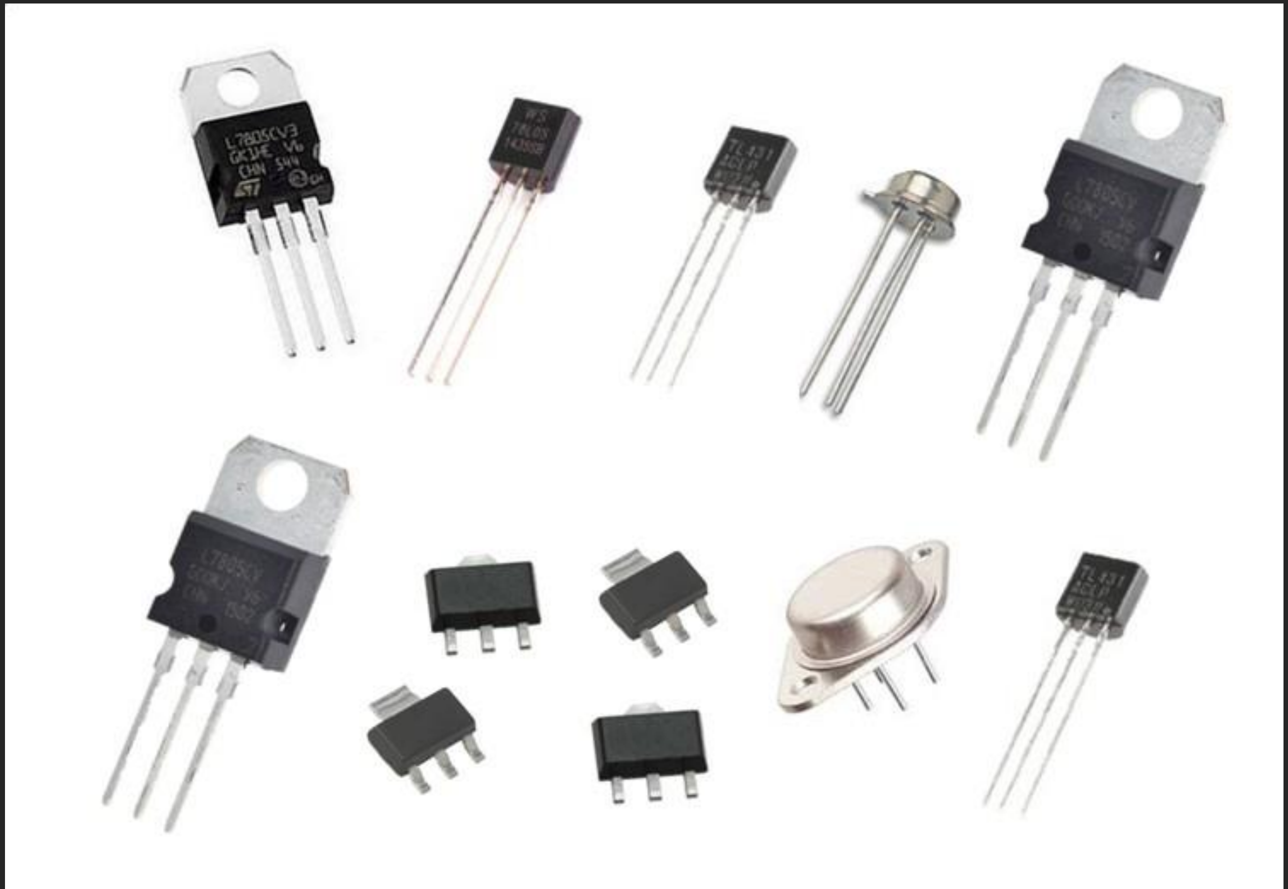




Voltage Regulators

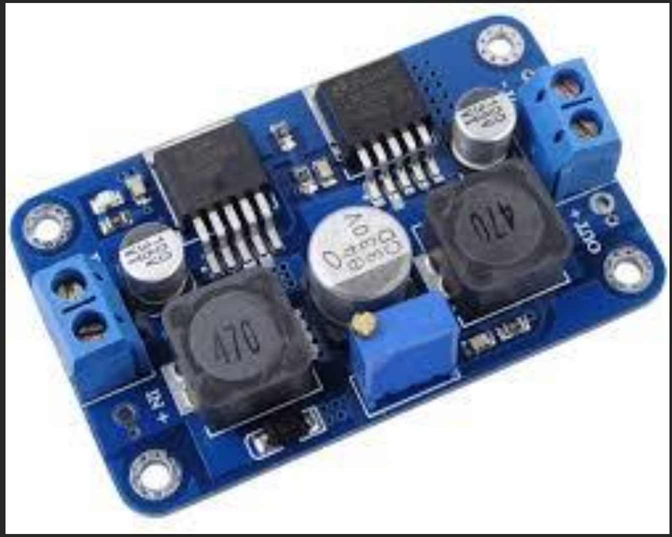
- Linear Voltage Regulator
  - Simple, but less efficient

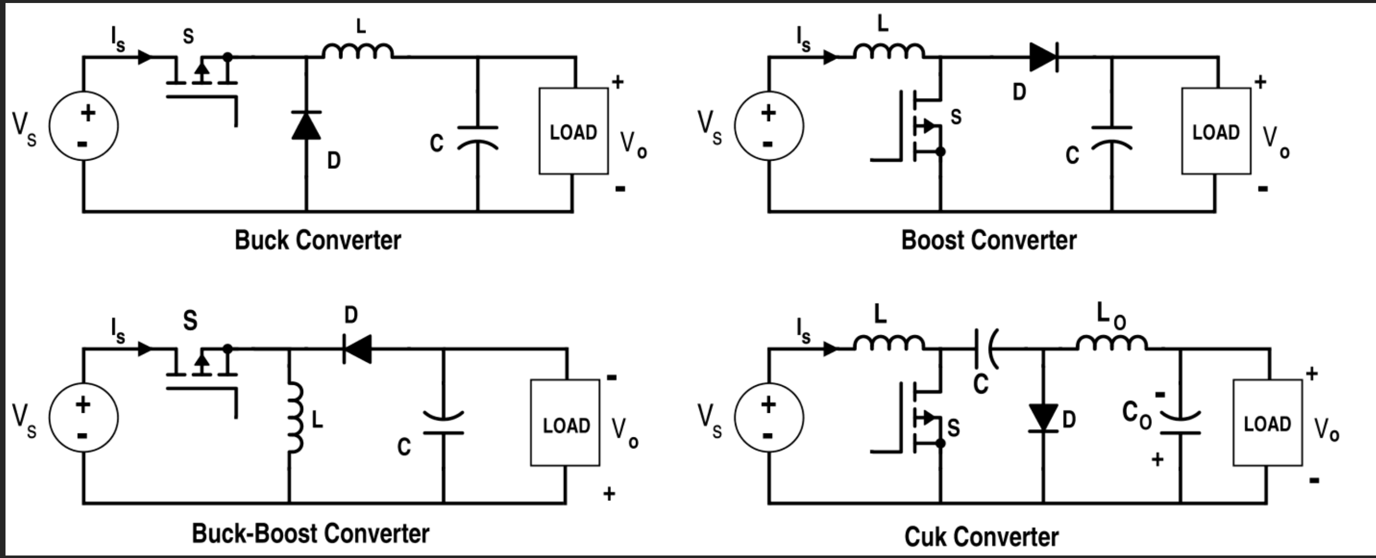




Voltage Regulators

- Switching Voltage Regulator
  - Buck – decreases the voltage
  - Boost – increases the voltage
  - Buck/boost – increases or decreases the voltage



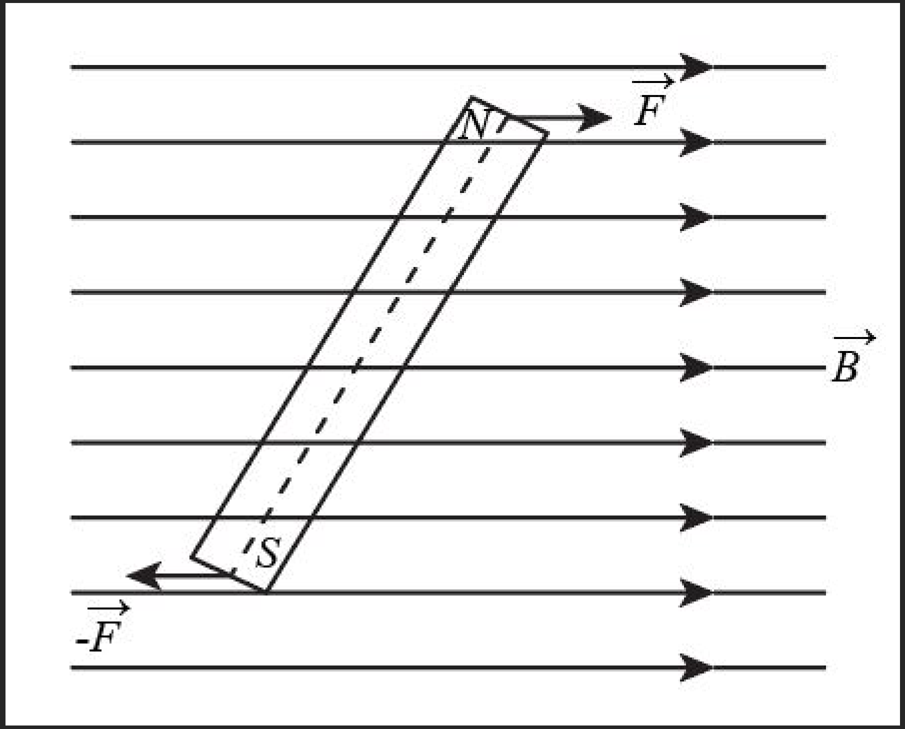


Actuators

Motors

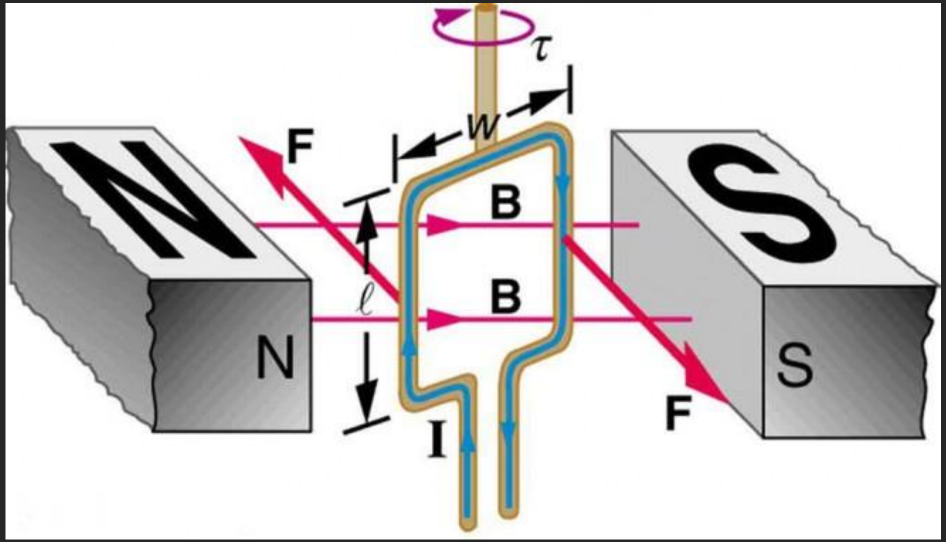
How do Electric Motors Work

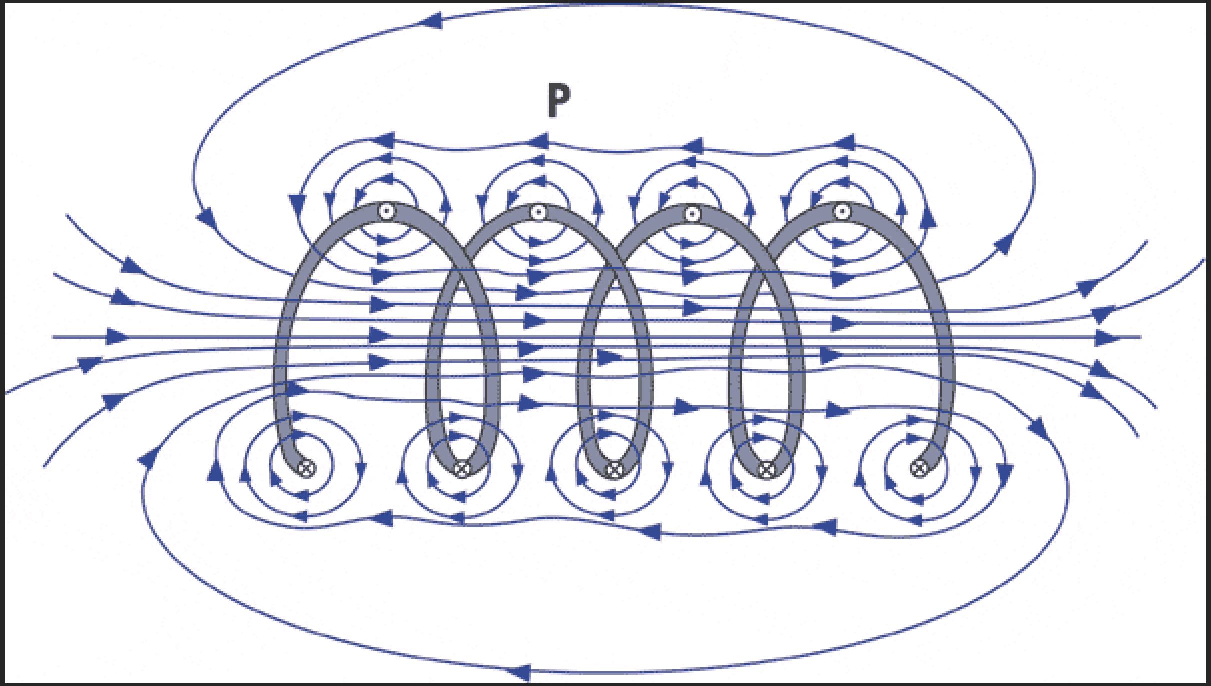
- Magnetic fields “like” to align
- $\vec{\tau} = \vec{m} \times \vec{B}$
- $\vec{m}$ = magnetic dipole moment



Magnetic Dipole of Wire Coil

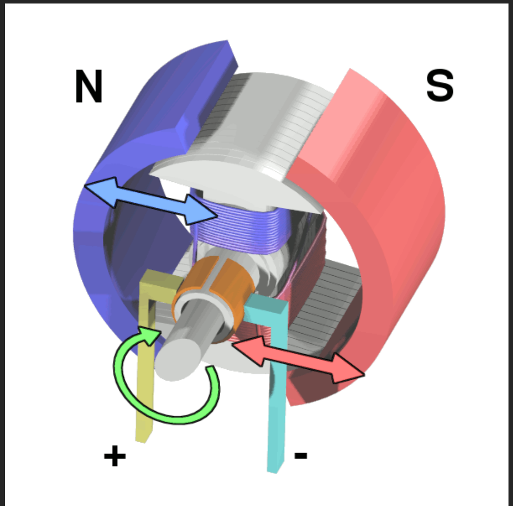
- $\vec{\tau} = \vec{m} \times \vec{B}$
- $m = NIA$
- $\vec{\tau} = NIAB\sin(\theta)$

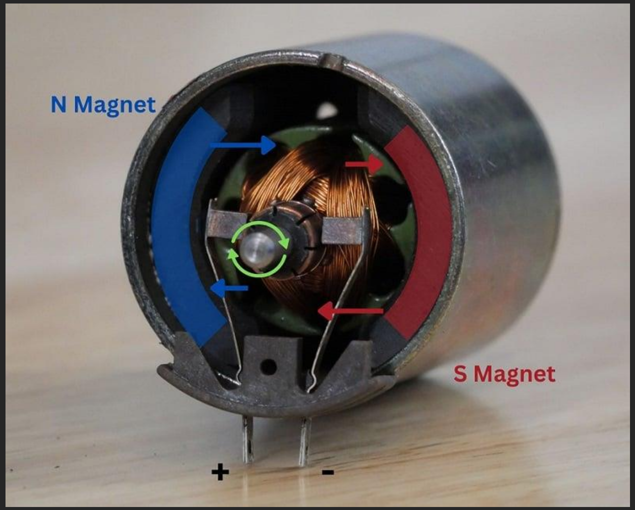


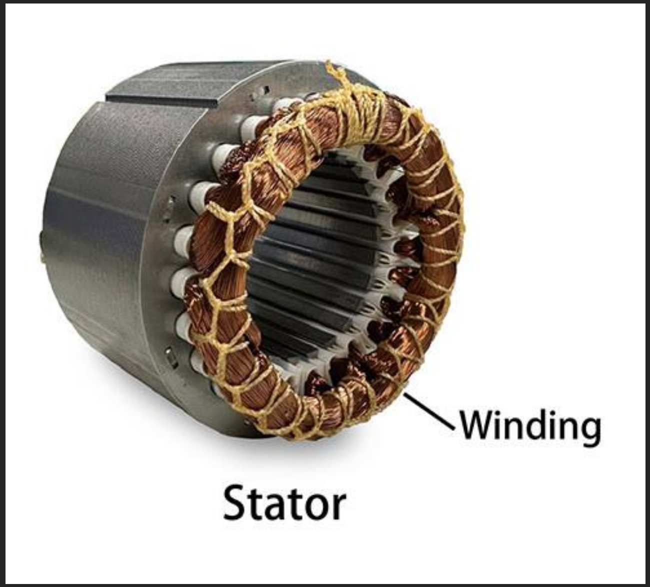


Motors – Stator

- Stator - The stationary part of the motor that produces a magnetic field
- DC motors - typically permanent magnets or windings
- AC motors - coils generating a rotating magnetic field

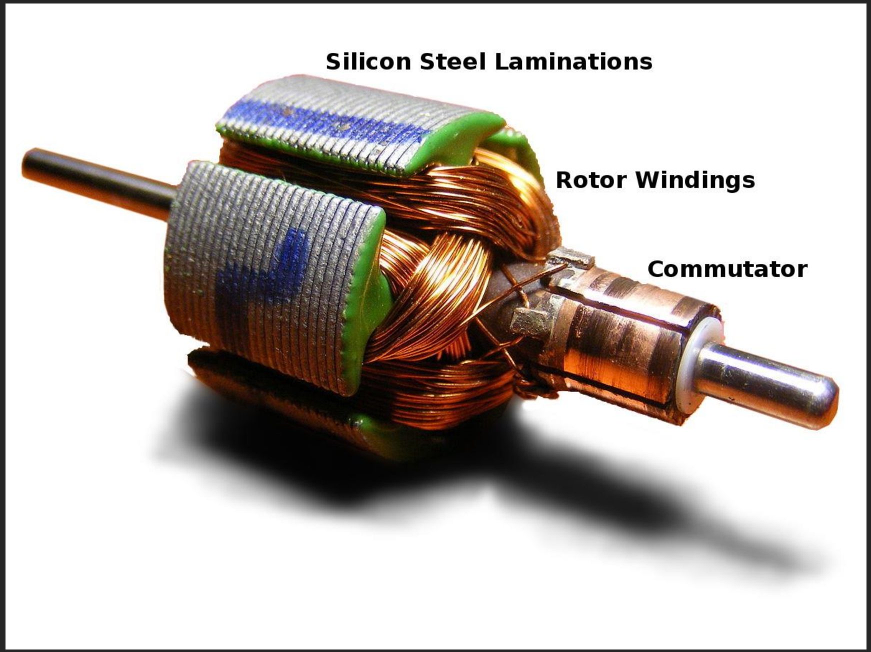


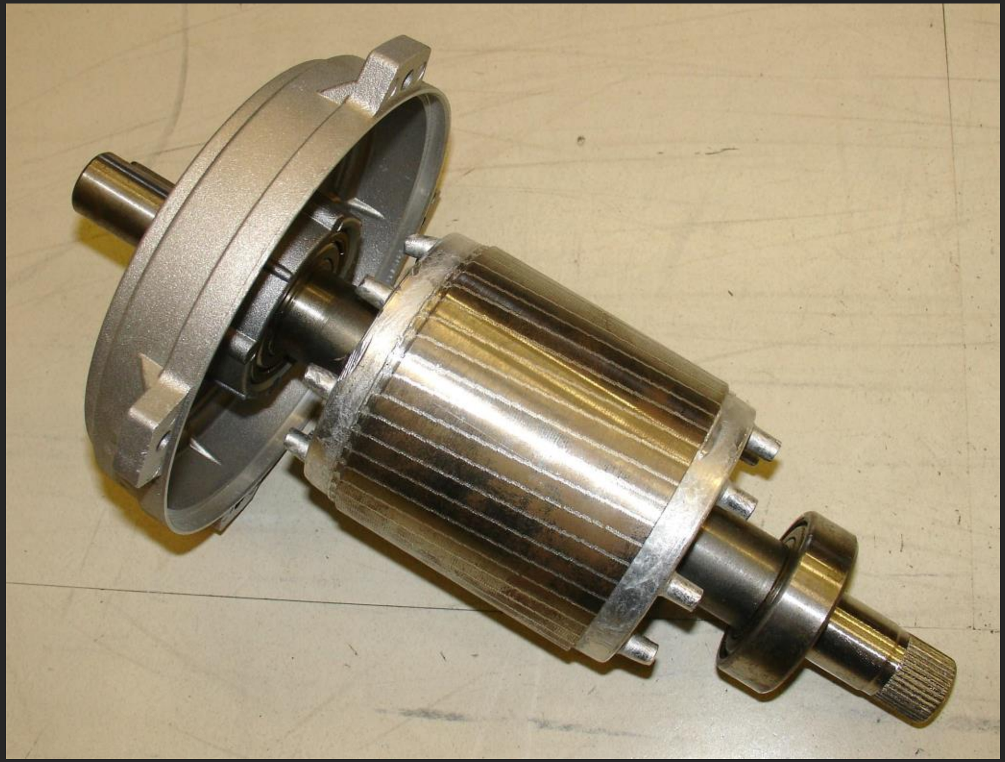




Motors – Rotor

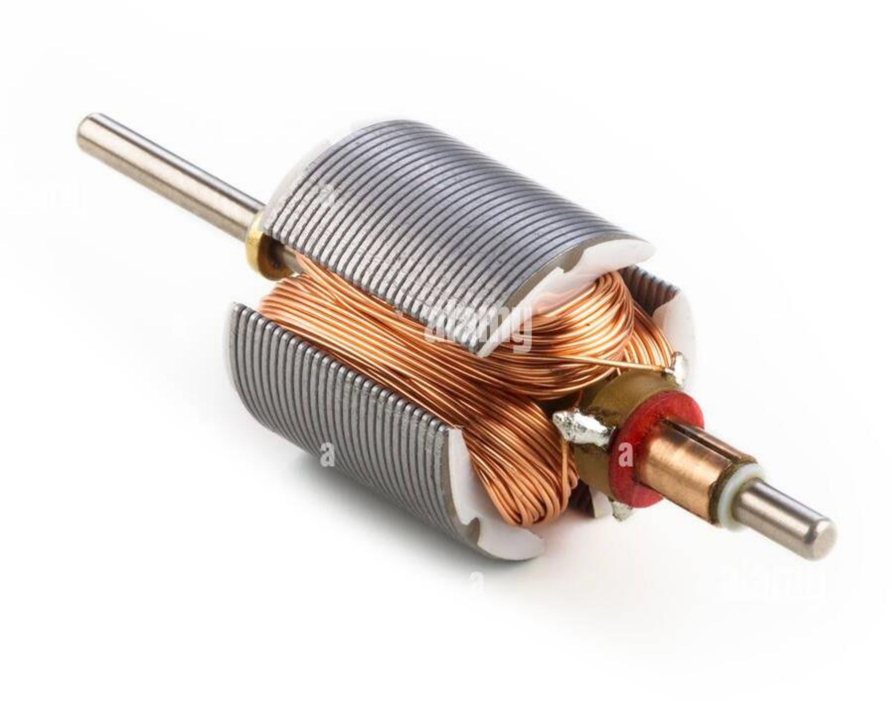
- Rotor – The rotating component inside the stator
  - It interacts with the stator's magnetic field to generate torque

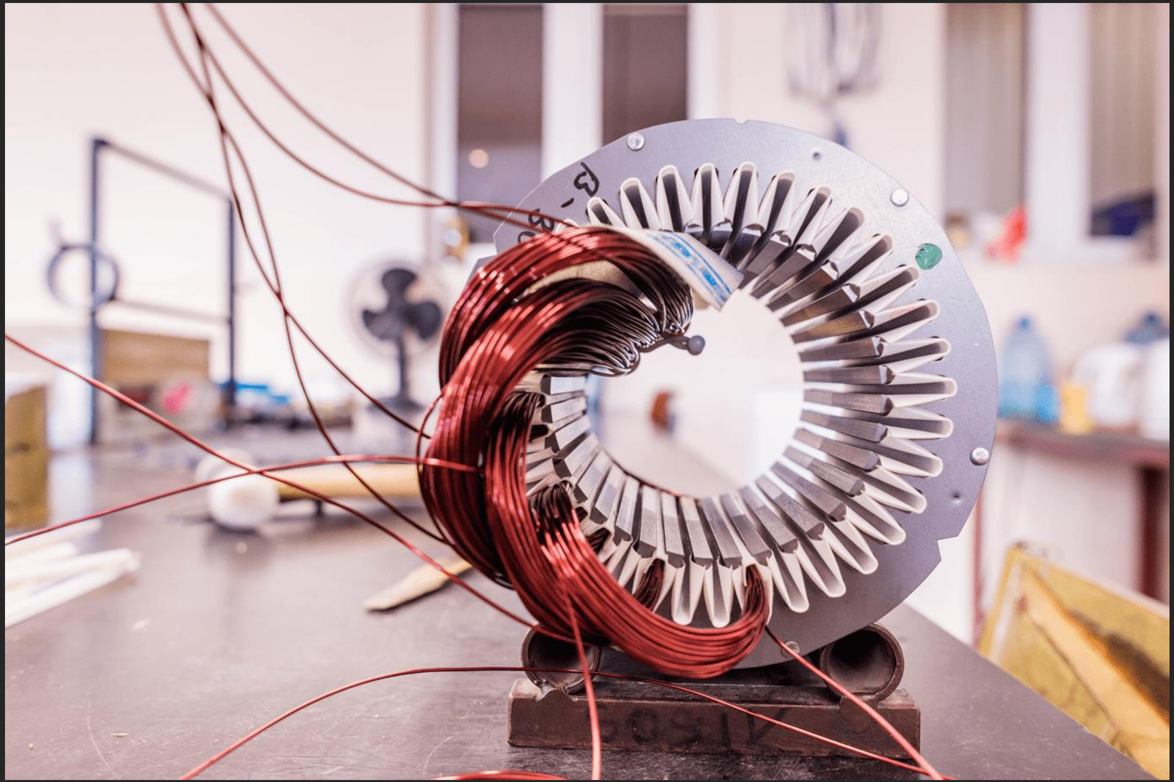




Motors – Windings

- Windings – Coils of wire that generate magnetic fields when current flows through them



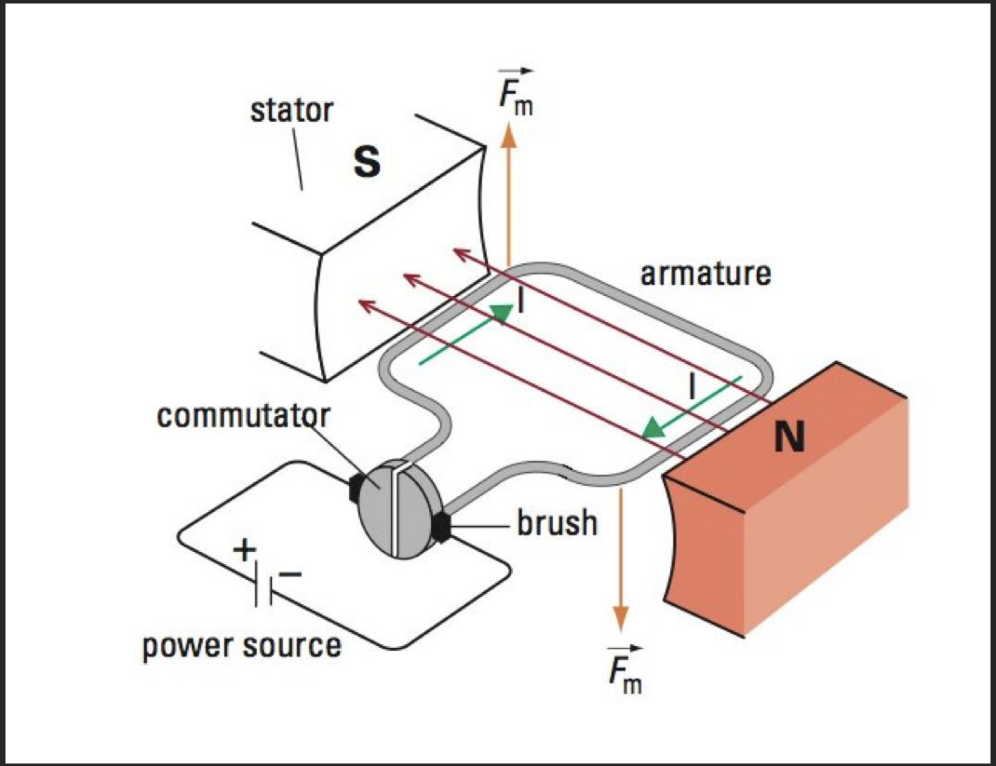


Motors – Armature

- Armature – The part of the motor that carries current and interacts with the magnetic field to generate motion
  - Windings are part of the armature
  - DC motors – Armature is usually in the rotor
  - AC Asynchronous motors – Armature is usually in the stator

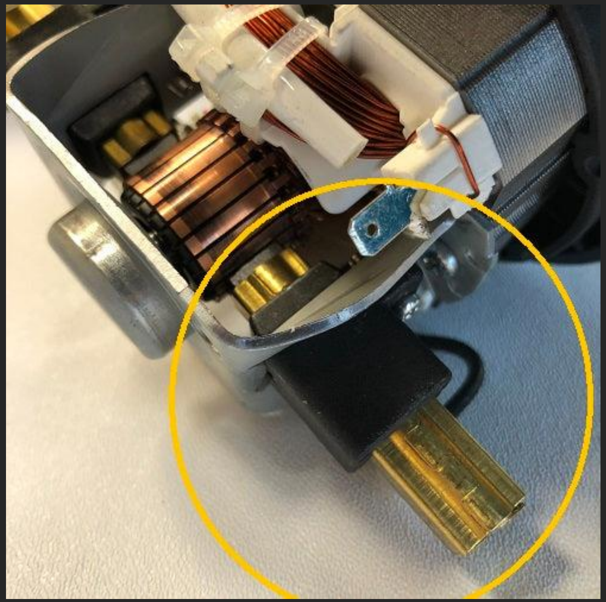
Motors – Commutator

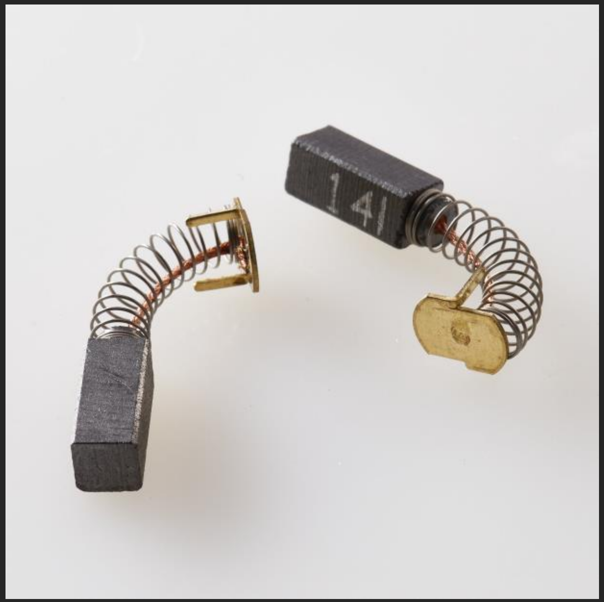
- Commutator – A segmented conductor in brushed DC motors that reverses current direction in the rotor windings

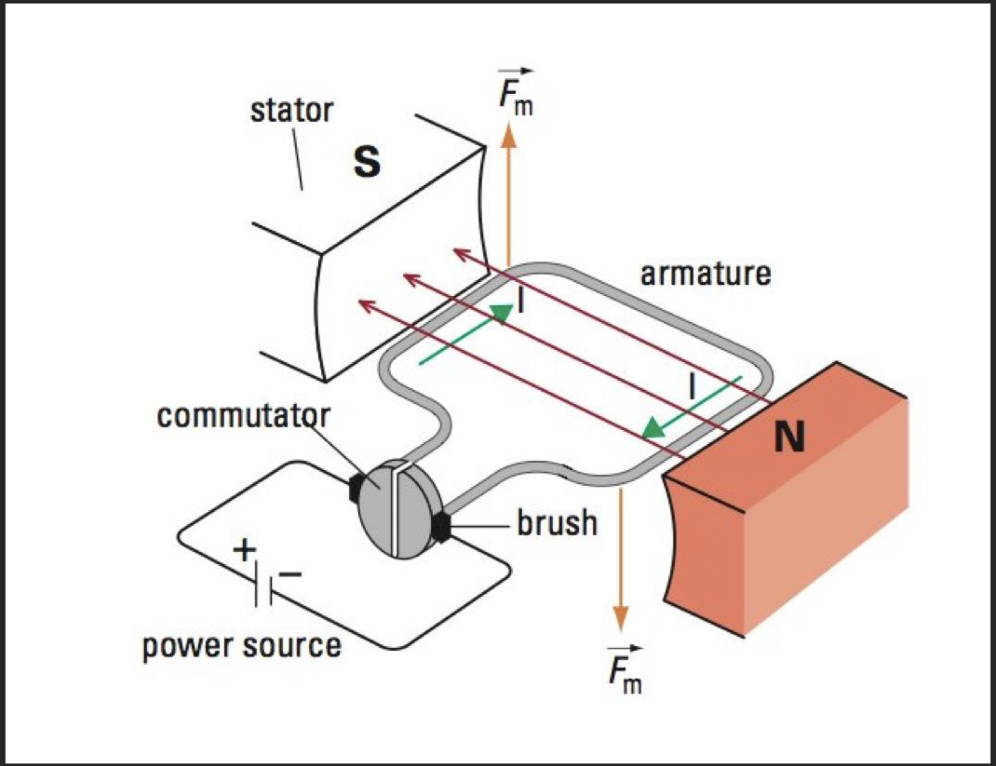


Motors – Brushes

- Brushes – Conductive carbon or metal elements in brushed DC motors that provide electrical contact with the commutator

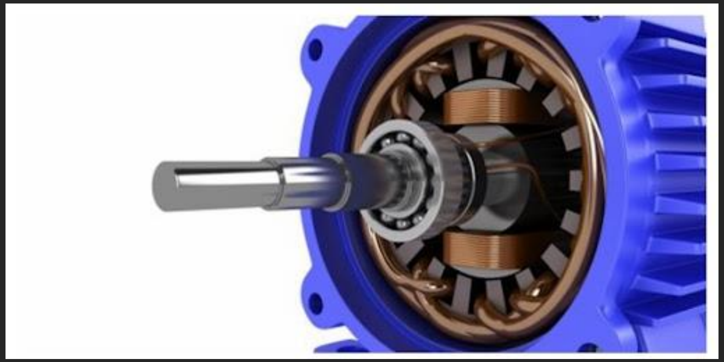


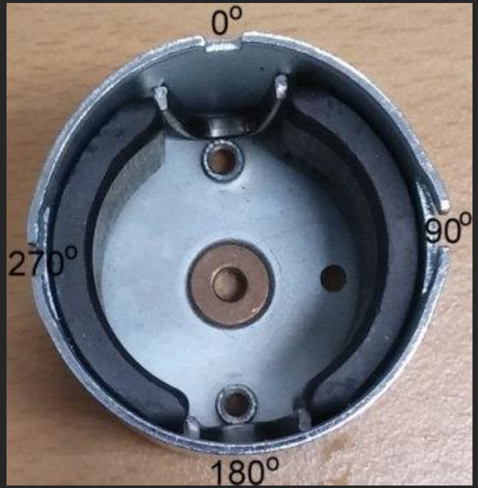




Motor

- Shaft – The rotating output of the motor that transfers mechanical energy to external components
- Bearings – Mechanical supports that allow the rotor to spin smoothly inside the motor housing, reducing friction
- Motor Housing (Frame) – The outer casing that protects internal components and aids in heat dissipation





Motor - Terminology

- Torque Constant (Kt) – Relationship between input current and torque, measured in Newton-meters per ampere (Nm/A)
  - Higher Kt means greater torque for the same current
- Speed Regulation Constant – How well a motor maintains its speed under varying loads
  - A lower value indicates better stability
- Back Electromotive Force – A voltage generated by a spinning motor that opposes the input voltage
  - It is proportional to speed and affects efficiency

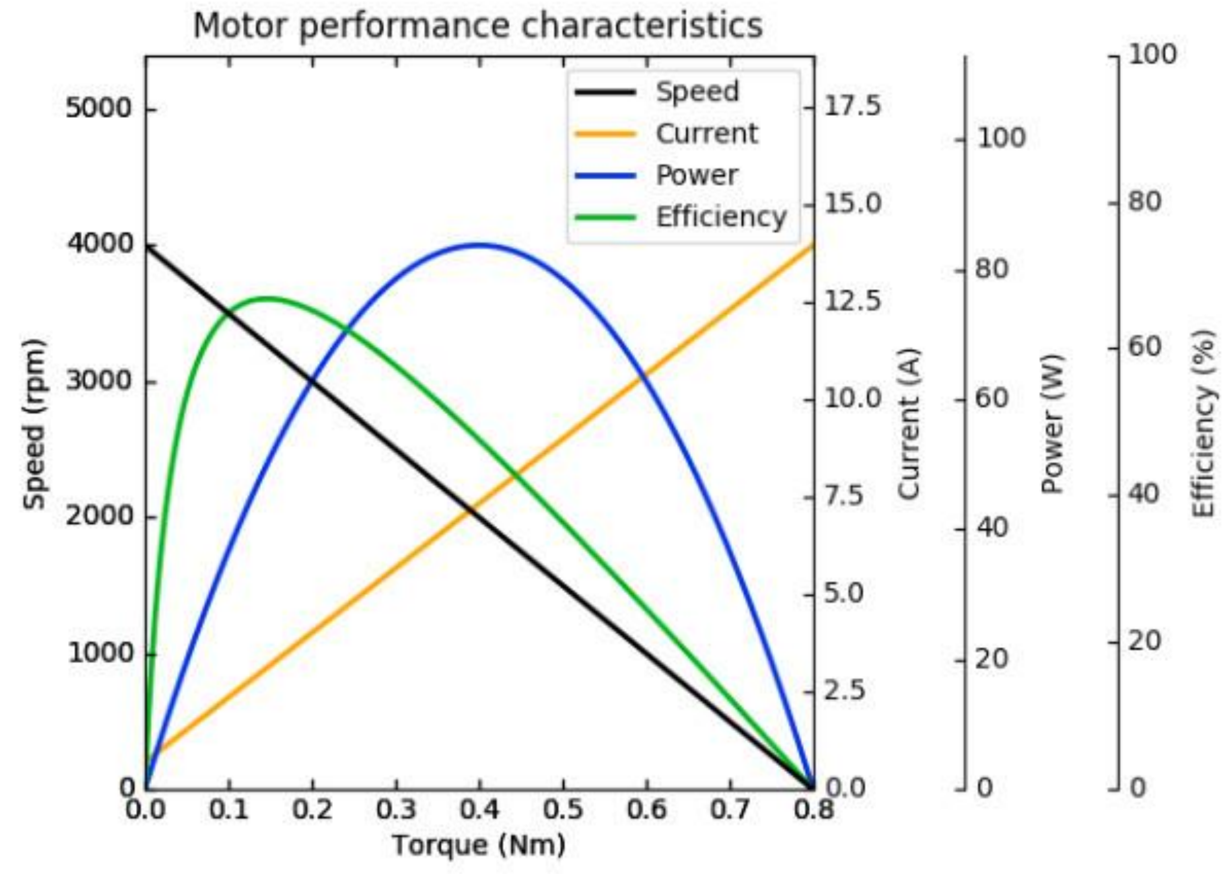
Motor - Terminology

- Power Factor – In AC motors, it represents the ratio of real power (useful work) to apparent power (total power drawn).
  - A higher power factor means better efficiency
- Slip – In AC induction motors, the difference between the synchronous speed (determined by supply frequency) and the actual rotor speed
  - expressed as a percentage

Motor Characteristics

- Efficiency – The ratio of mechanical output power to electrical input power
  - Higher efficiency means less energy loss as heat
- Starting Torque – The initial torque a motor can generate when starting from rest
  - Important in applications like electric vehicles and industrial machinery
- Maximum Torque (Pull-Out Torque) – The highest torque an AC motor can produce before losing synchronism

Motor Characteristic Curve – DC Motors



Parameter	Units	Value
Nominal voltage	V	24
No-load speed	rpm	4000
No-load current	A	0.7
Rated speed	rpm	3270
Rated torque	Nm	0.15
Rated current	A	3.1
Stall torque	Nm	0.80
Starting current	A	14.0
Max power	W	84
Max efficiency	%	67
Terminal resistance	Ω	1.7
Torque constant	Nm/A	0.057
Speed constant	rpm/V	167
Back-emf constant	V/rpm	0.006

Motor Characteristic Curve – DC Motors

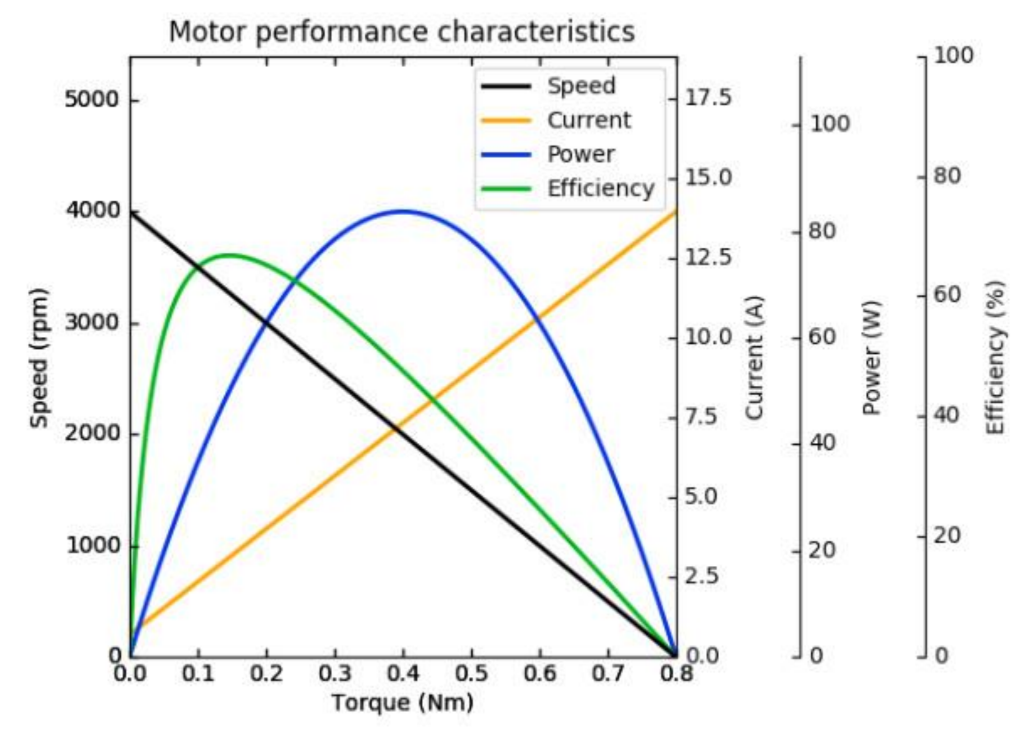
- Torque vs. Speed
  - No-load Speed: At zero torque (no load), the motor runs at its maximum speed
  - Stall Torque: At zero speed, the motor produces its maximum torque (stall torque)
- $T = T_{stall}\left(1 - \frac{N}{N_{no-load}}\right)$

$$T = \text{Torque} \qquad T_{stall} = Stall\ Torque$$

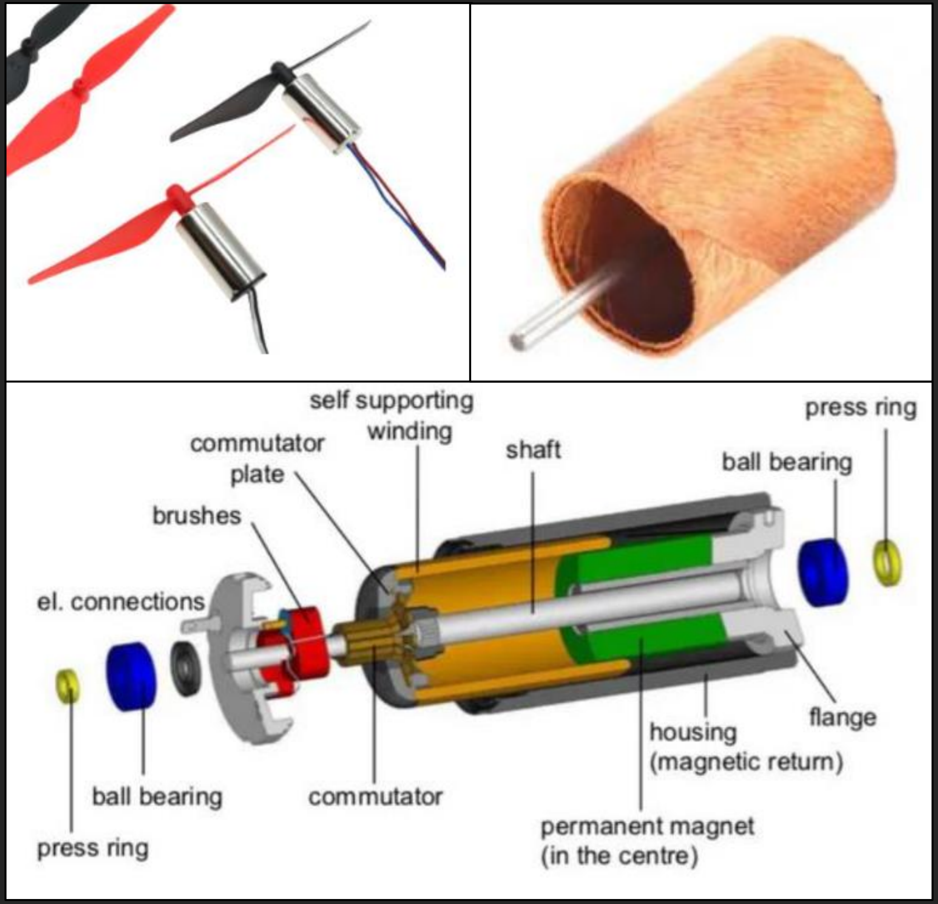
$$N = \text{Speed} \qquad N_{no-load} = No\ Load\ Speed$$

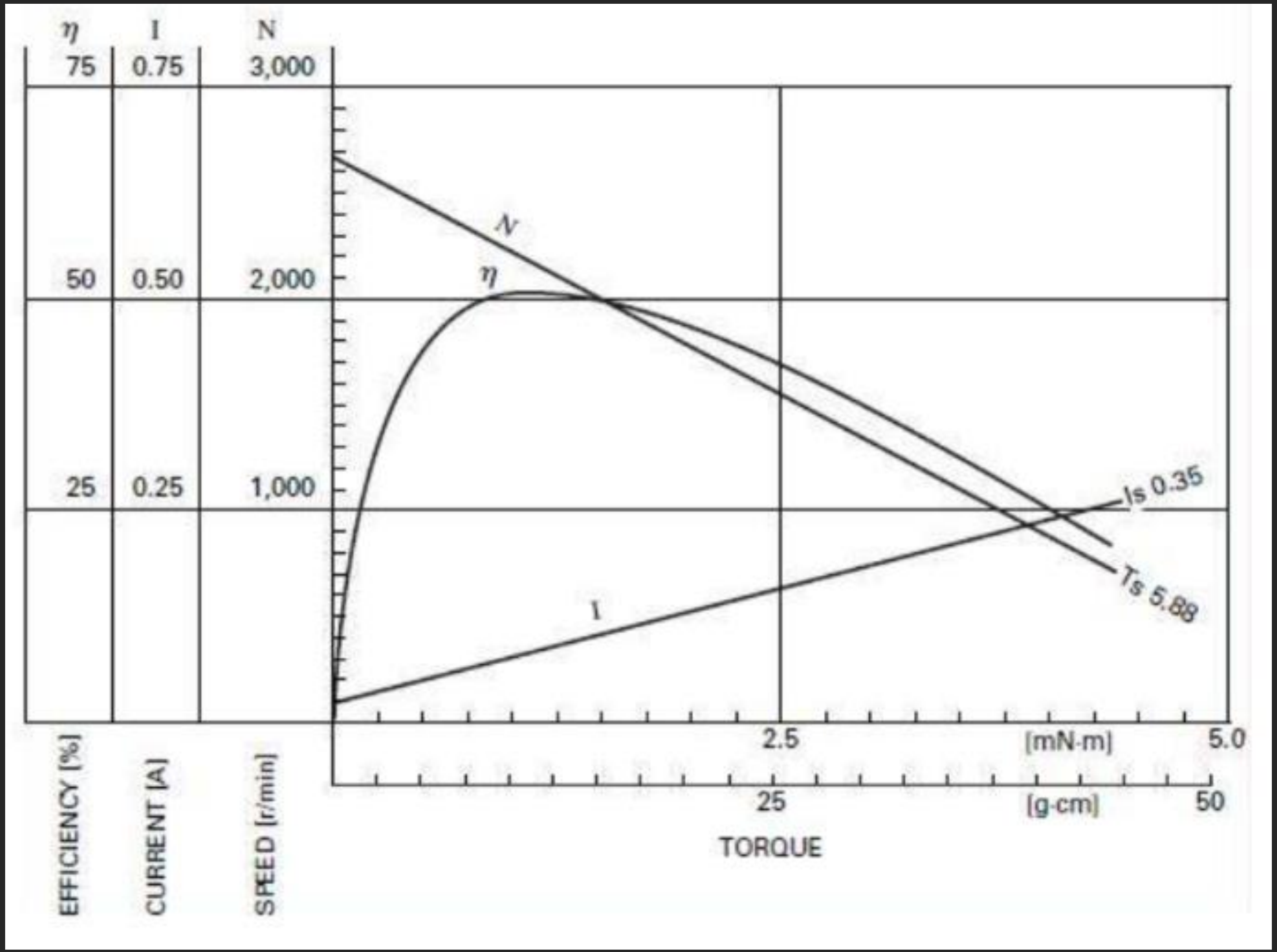
Motor Characteristic Curve – DC Motors

- As the load increases, the speed decreases, and the armature current increases
- $N = N_{no-load} - k_N I_a$
- k_N = Speed regulation constant



Example – 720 Coreless Brushed DC Motor





Motor Characteristic Curve – AC Motors

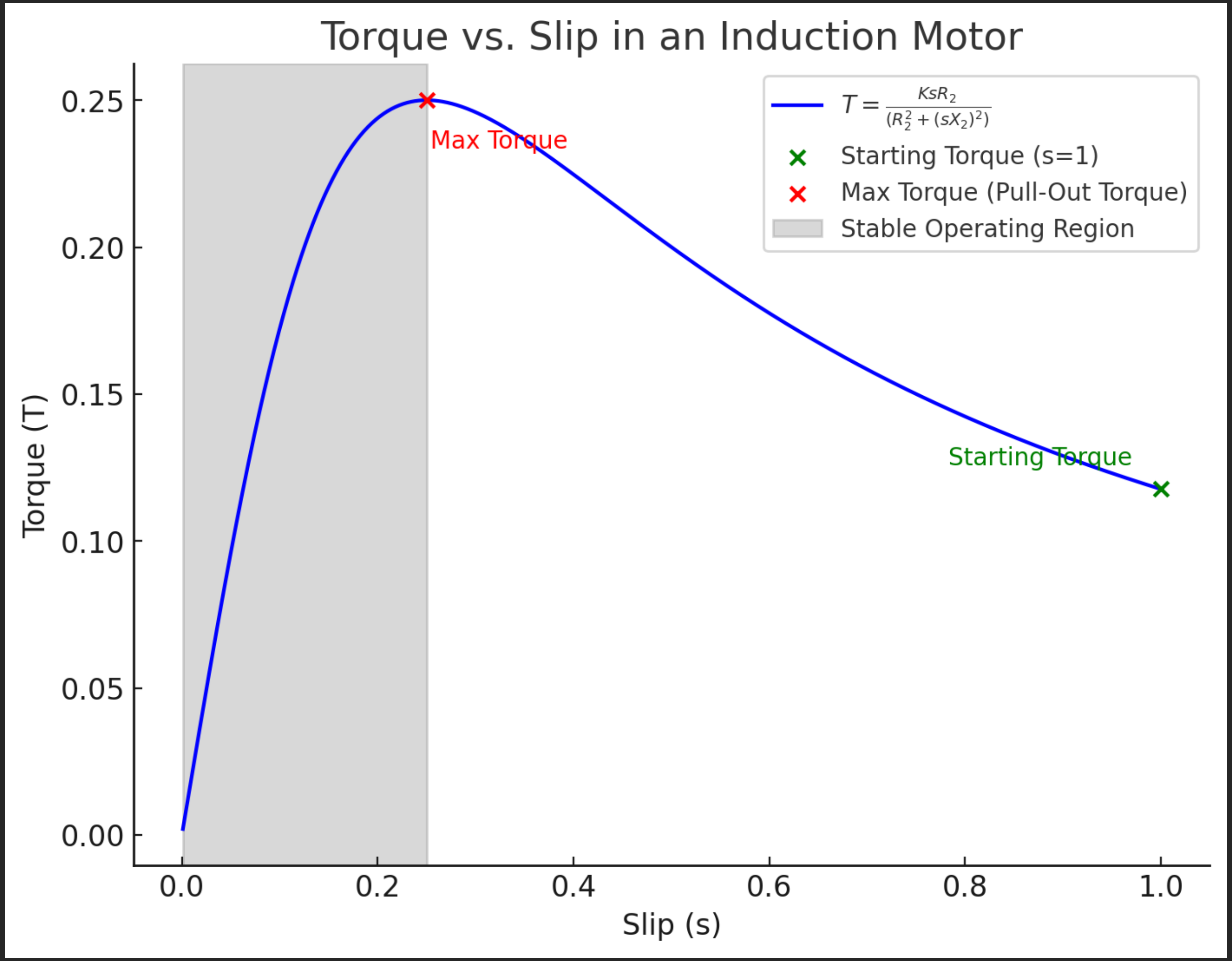
- Slip is the relative speed difference between the rotor and the rotating magnetic field
- $s = \left(\frac{\mathrm{N}_s - N}{N}\right)$
- $s =$ Slip
- $\mathrm{N}_s =$ Synchronous speed

Motor Characteristic Curve – AC Motors

- Torque vs Slip
  - Starting Torque: At maximum slip
  - Stable Operating Region: Between zero slip and the slip at maximum torque
- $T = \frac{KsR}{R+(sX)^2}$
- K = constant proportional to square of the voltage
- R = armature resistance
- X = armature reactance

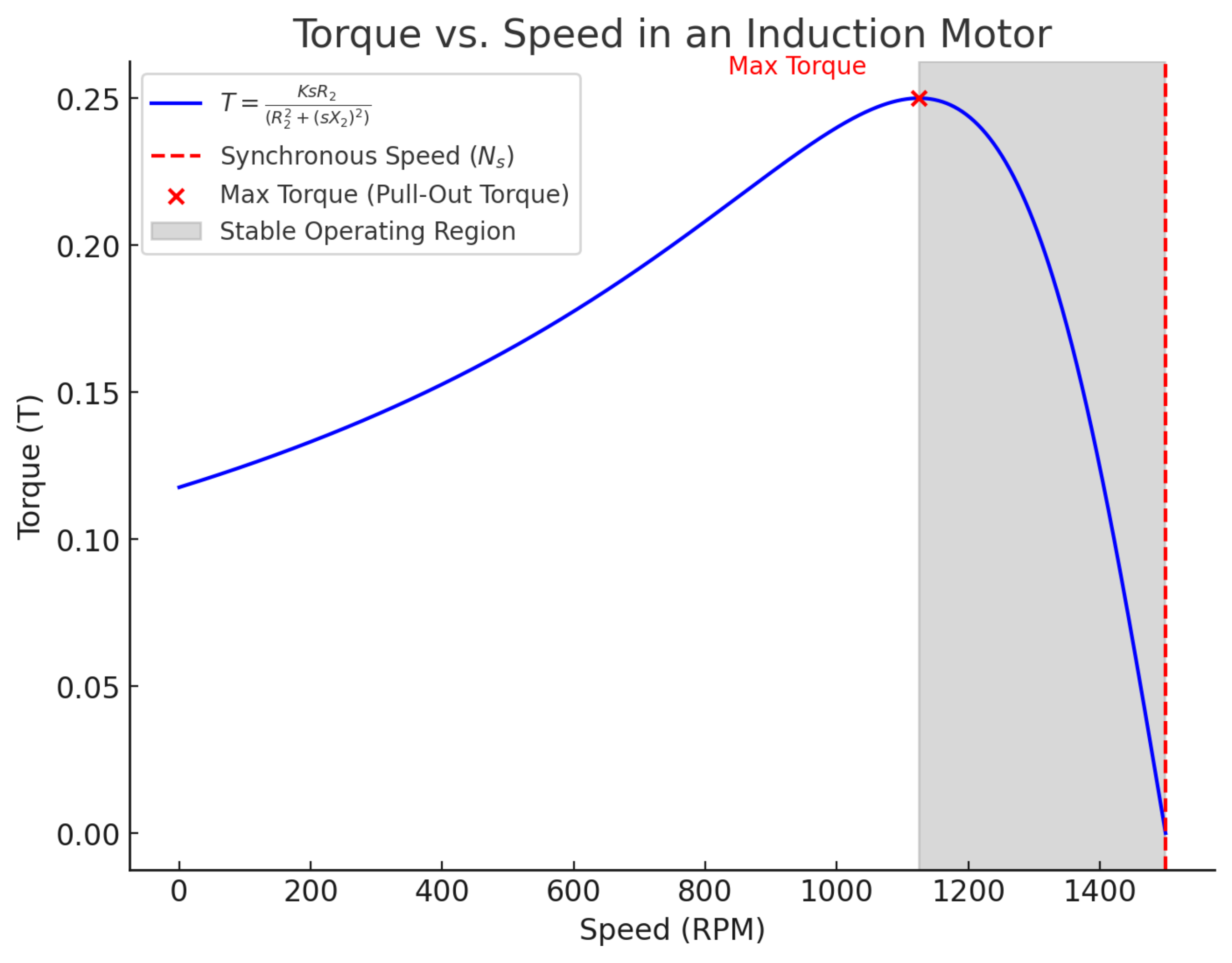
Motor Characteristic Curve – AC Motors

- $T = \frac{KsR}{R+(sX)^2}$

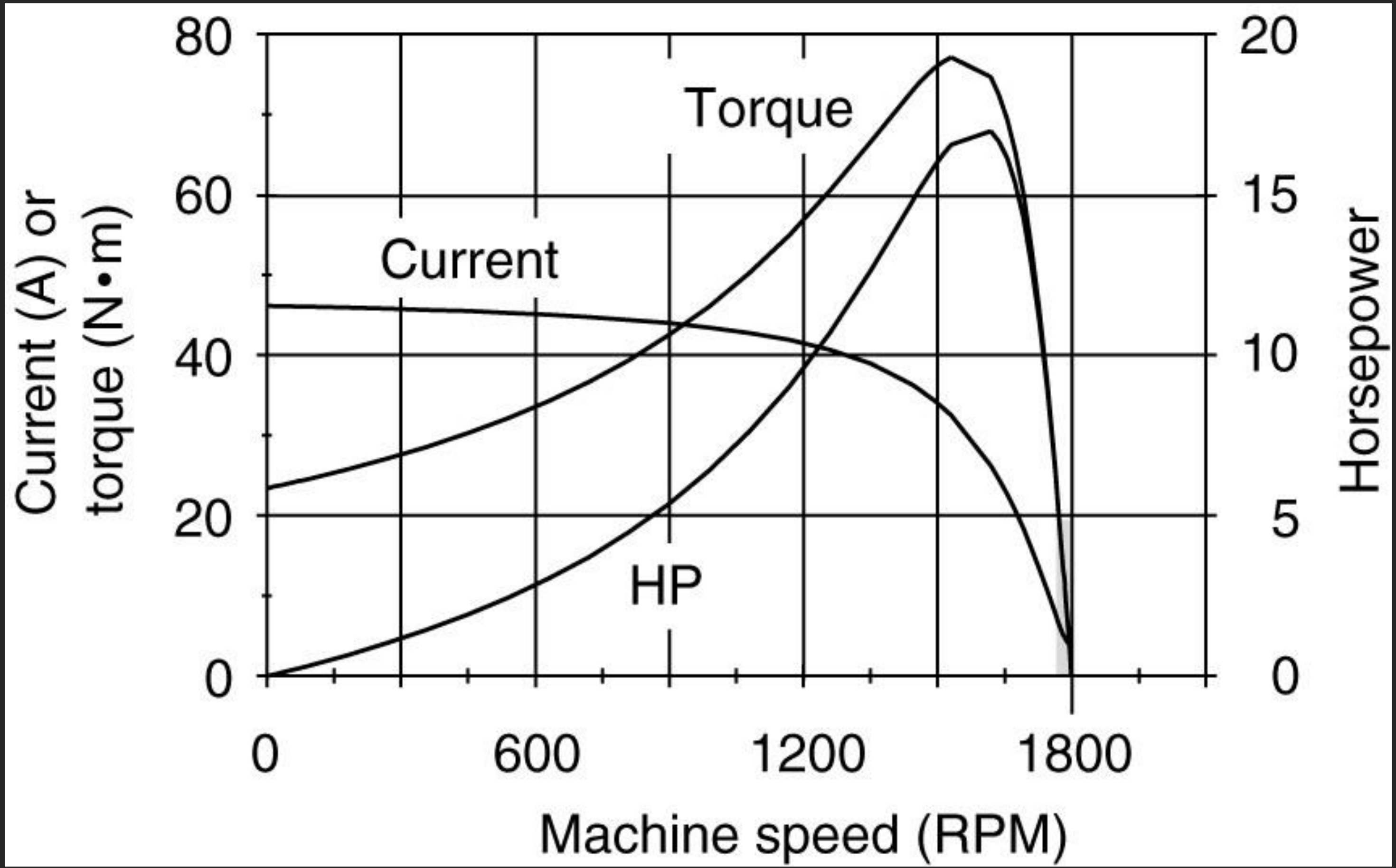


Motor Characteristic Curve – AC Motors

- Torque Vs Speed
- $s = \left(\frac{N_s - N}{N}\right)$
- $T = \frac{KsR}{R+(sX)^2}$



Motor Characteristic Curve – AC Motors

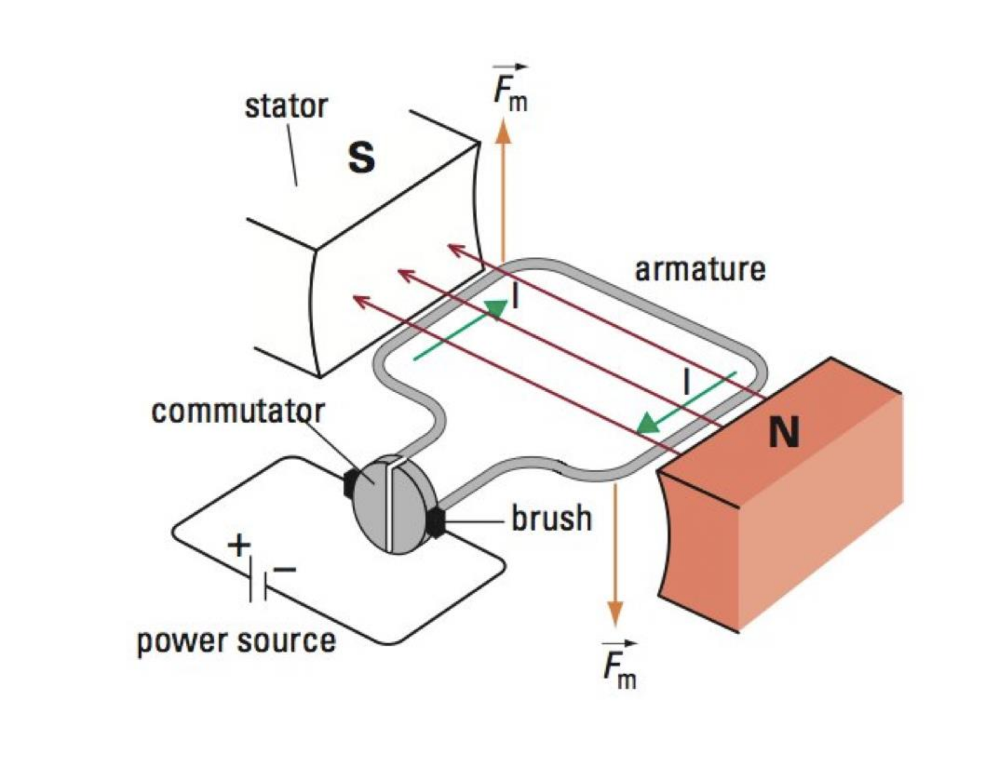


Motor Taxonomy

- DC Motors
  - Brushed
    - Coreless
  - Brushless
  - Stepper Motors
- AC Motors
  - Synchronous
  - Asynchronous (Induction)
- Servos & Special Purpose Motors

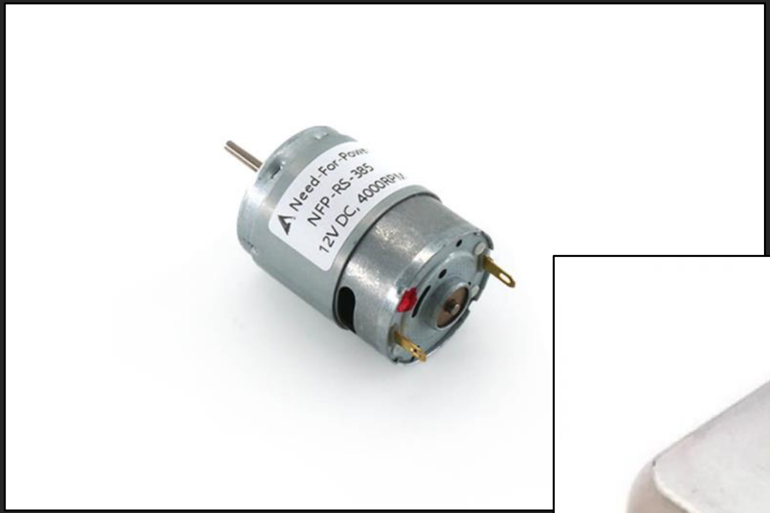
Brushed DC Motors

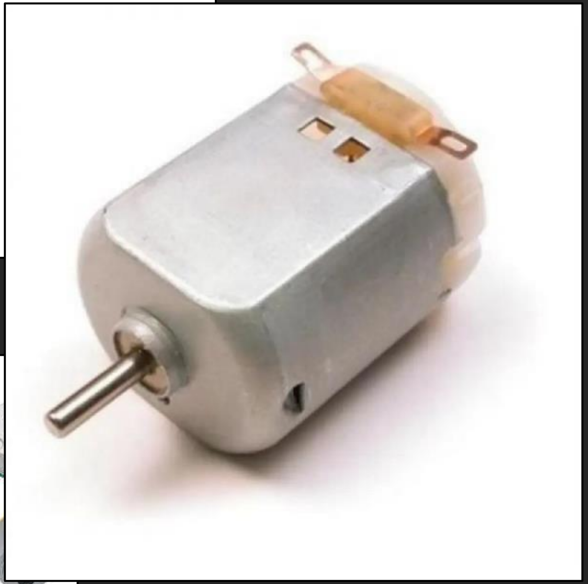
- Stator – permanent magnets (sometimes electromagnetic)
- Rotor – electromagnetic coils
- Operating principle
  - Current flows through armature windings
  - Magnetic field interacts with stator magnets
  - Commutator reverses the field when the rotor turns



Brushed DC Motors

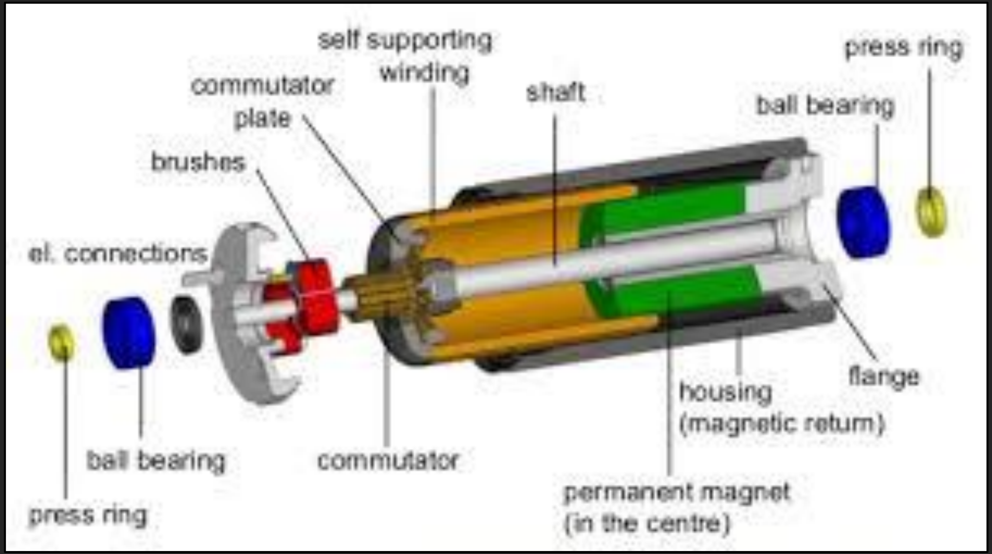
- Advantages
  - Simple seed control
  - High starting torque
  - Low-cost easy to manufacture
- Disadvantages
  - Requires maintenance
  - Electrical noise
  - Efficiency and lifespan





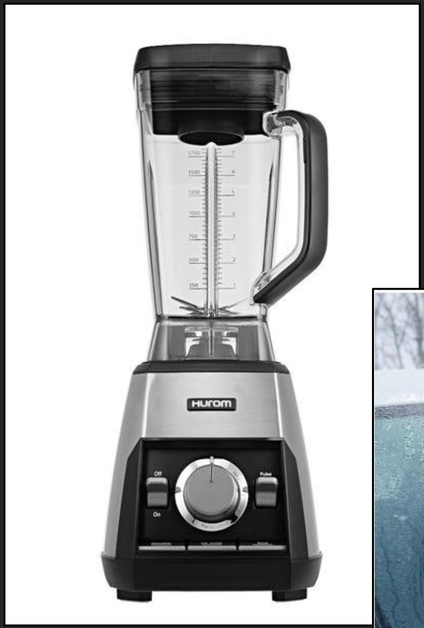
Coreless Brushed DC Motors

- Most DC motors have heavy metal cores in between rotor coils
  - Higher torque density, thermal dissipation, cost effective,
  - Higher inertia, eddy current loss
- Coreless brushed motors do not have iron in their stator
  - Lower inertia, higher efficiency, good low-voltage performance
  - Lower torque density, more expensive



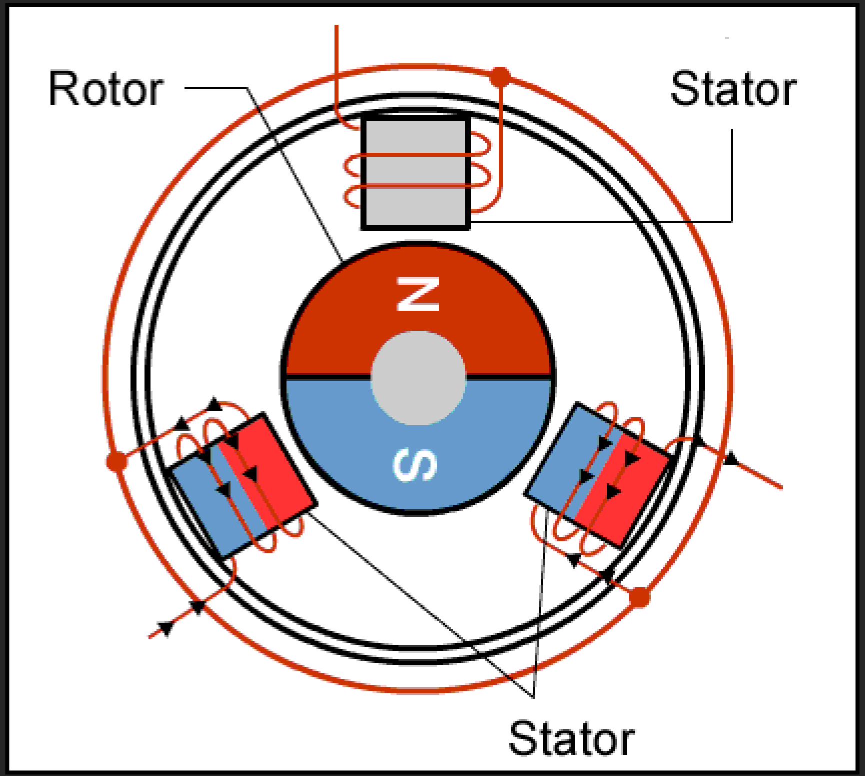
Brushed DC Motors

- “Low-end” DC Motors
- Consumer goods and automotive
  - Power tools, toys, windshield wipers, starter motors, fans
- Robotics
  - Servos, mobility
- Medical
  - Surgical tools, infusion pumps, wheelchairs

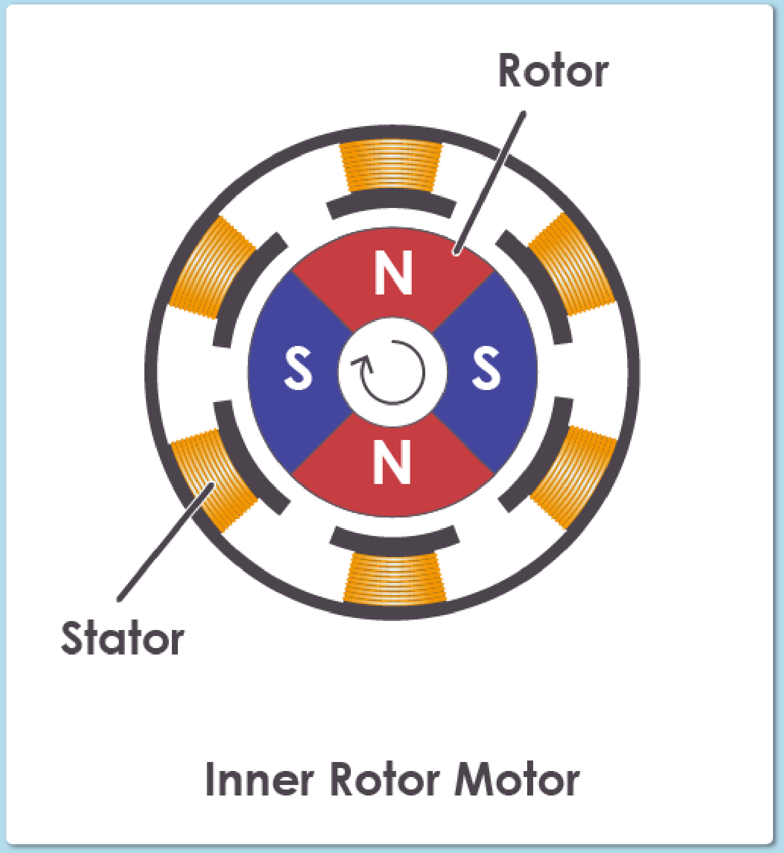


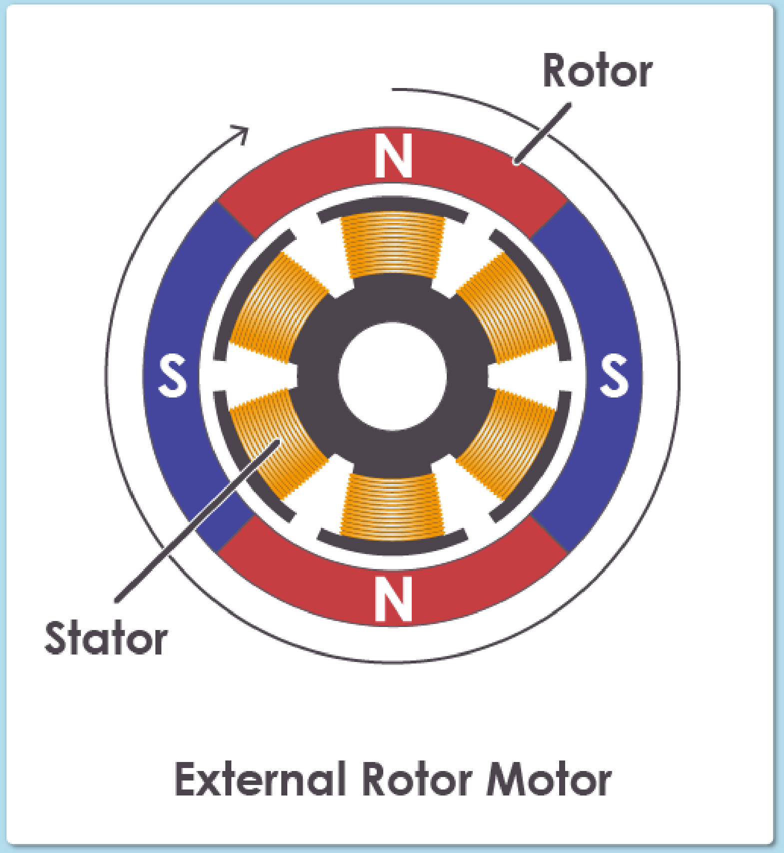
Brushless DC Motors

- Stator – Electromagnetic coils
- Rotor – Permanent magnets
- Operating Principle
  - Electronic controllers switch current to create moving magnetic field
  - Permanent magnets on the rotor follow the magnetic field
  - Position of the rotor is monitored with a sensor



Inner Rotor Vs Outer Rotor





Brushless DC Motors

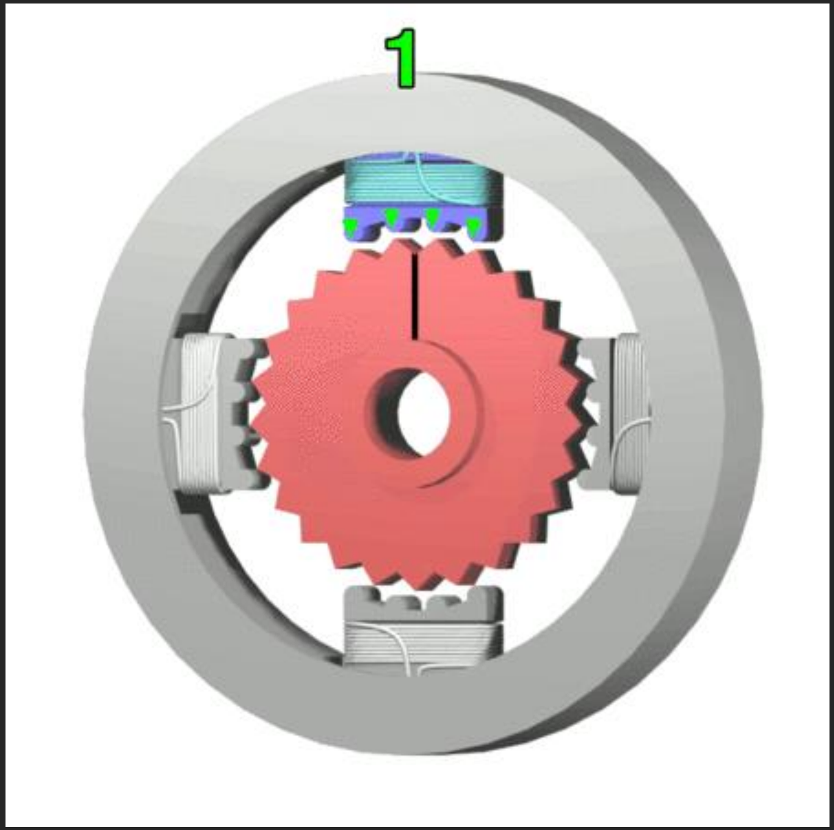
- Advantages
  - Higher efficiency and reliability
  - Lower maintenance requirements
  - Better speed-torque characteristics and higher speed ranges
  - Reduced electrical noise compared to brushed motors
- Disadvantages
  - Higher initial cost due to the need for electronic controllers
  - More complex control algorithms required for operation
  - Potential issues with electromagnetic interference (EMI) from the electronic controllers

Brushless DC Motors Applications

- Anywhere you are willing to spend more money to get a “better”, higher efficiency, higher power, higher precision control DC motor.
- Industrial manufacturing
- Medical
- Robotics
- Consumer product

Stepper Motor

- Similar to a brushless DC motor, but moves in discrete steps, enabling precise positioning control
- Can “hold” a position
- Uses teeth to line up precise angles
- More windings = More control



Stepper Motor

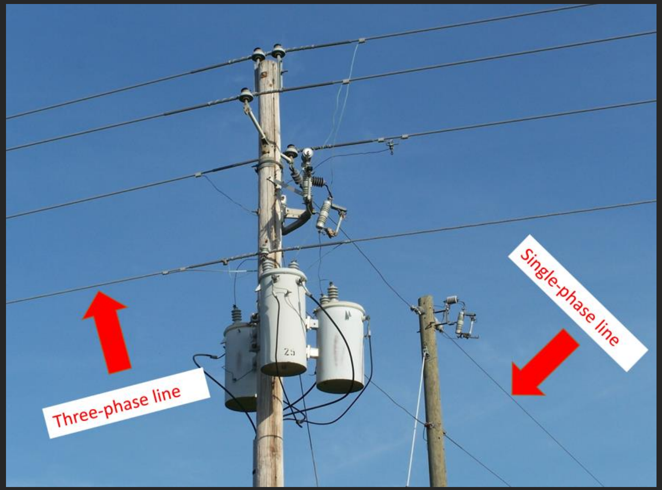
- Advantages
  - Precise control of position and speed without the need for feedback systems
  - High torque at low speeds, making them suitable for holding applications
  - Simple and rugged construction with long operational life
- Limitations
  - Lower efficiency due to continuous power consumption
  - Limited high-speed performance and potential for resonance issues
  - Requires a dedicated driver circuit to manage the step sequence

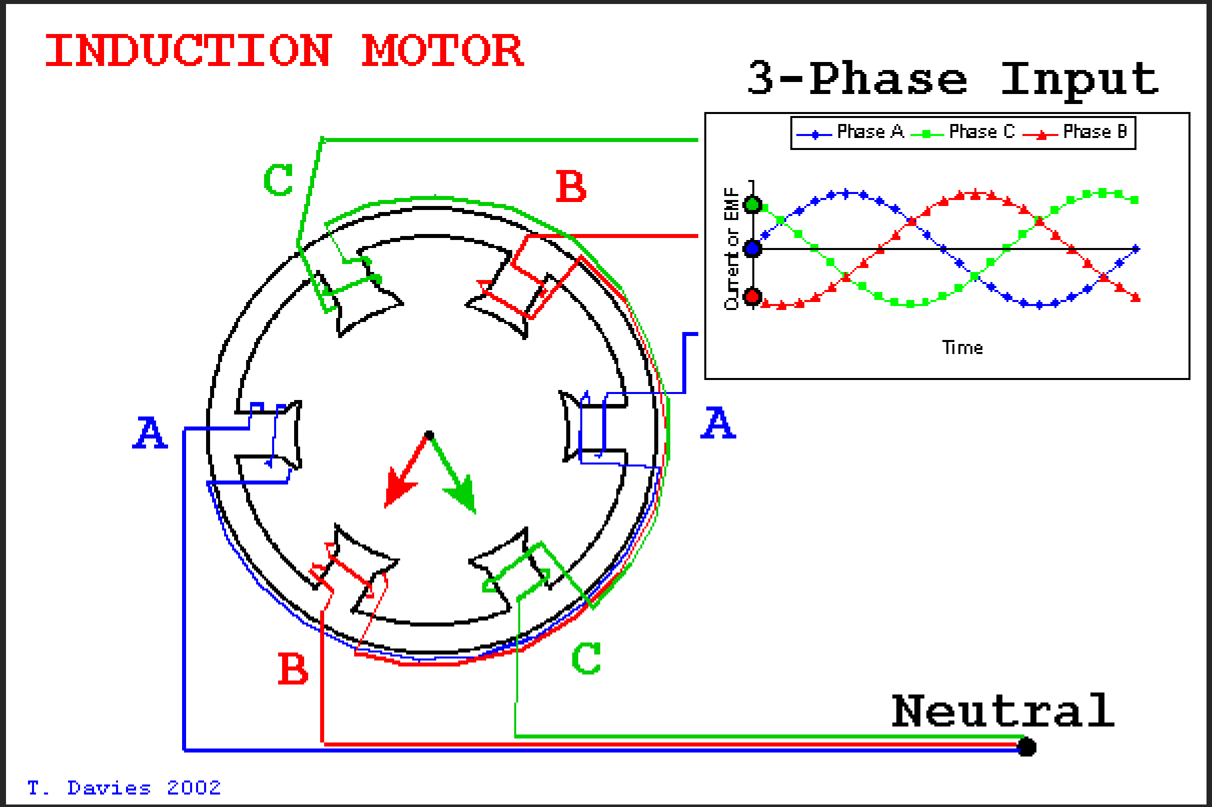
Stepp Motor - Applications

- CNC Machines – Used in computer numerical control (CNC) routers, laser cutters, and milling machines for precise motion
- Robotic Arms – Enable fine movement control in industrial and service robots
- Factory Automation –conveyor belts, pick-and-place machines, and packaging systems

Asynchronous (Induction) AC Motors

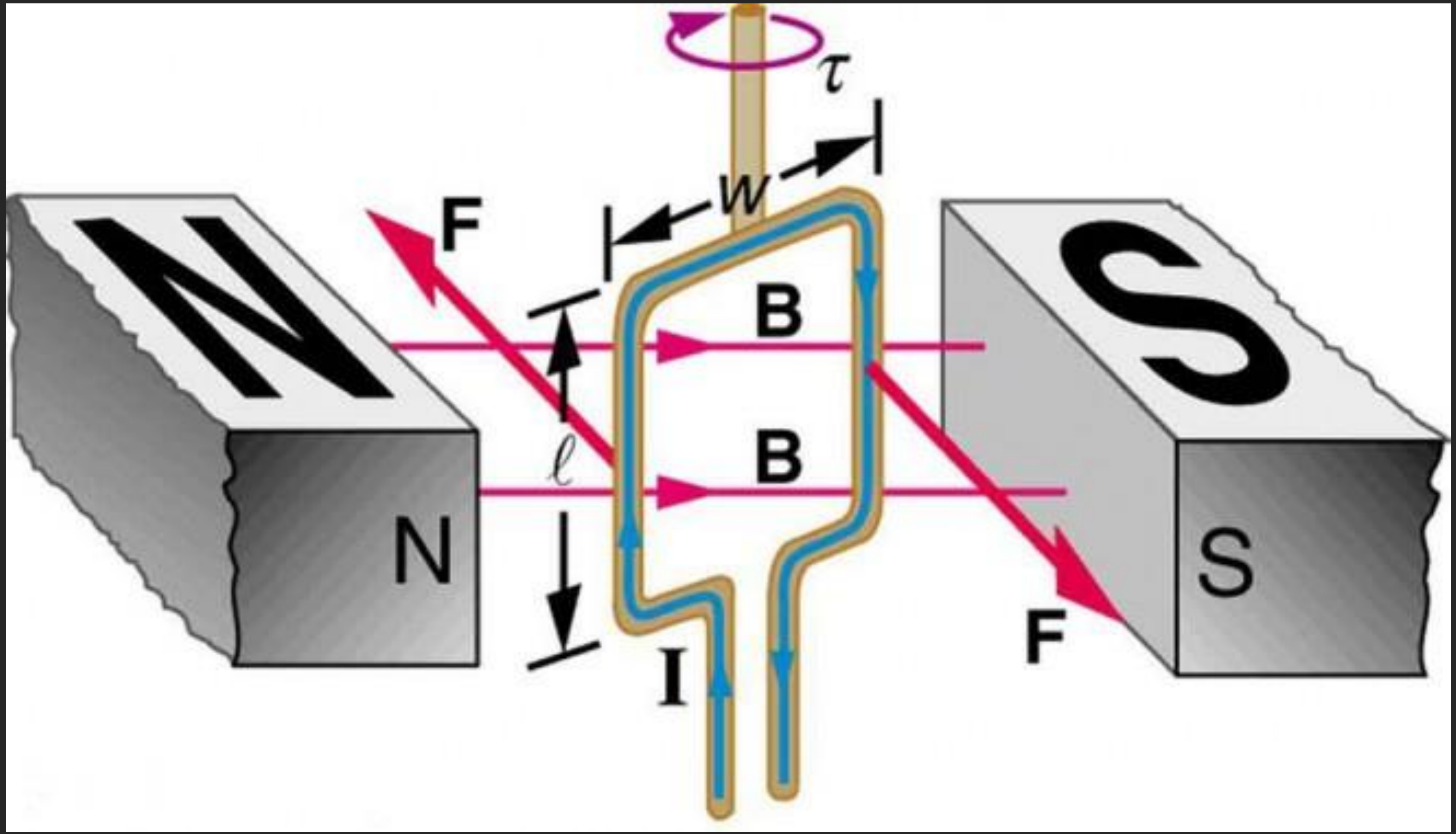
- 3-Phase induction motor
  - LL: 208V, LN:120V
- Creates a "rotating" magnetic field



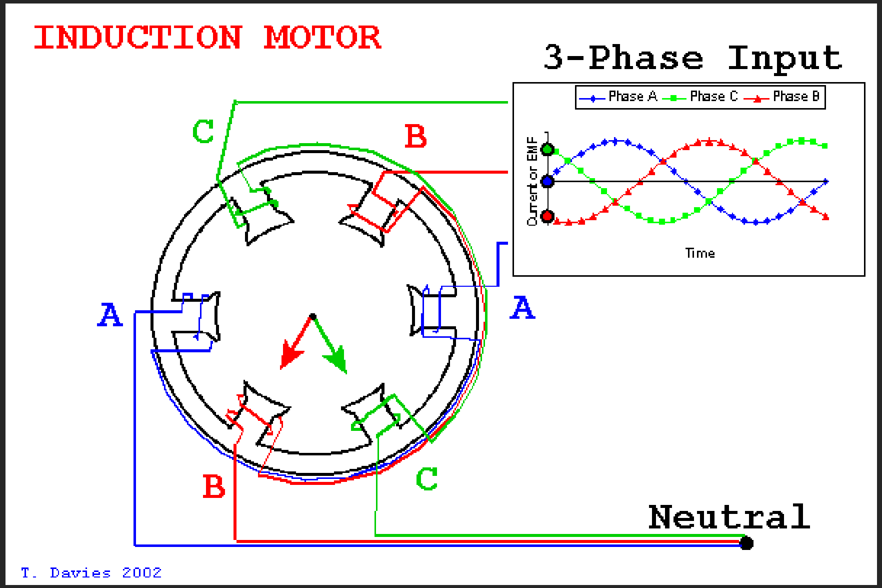


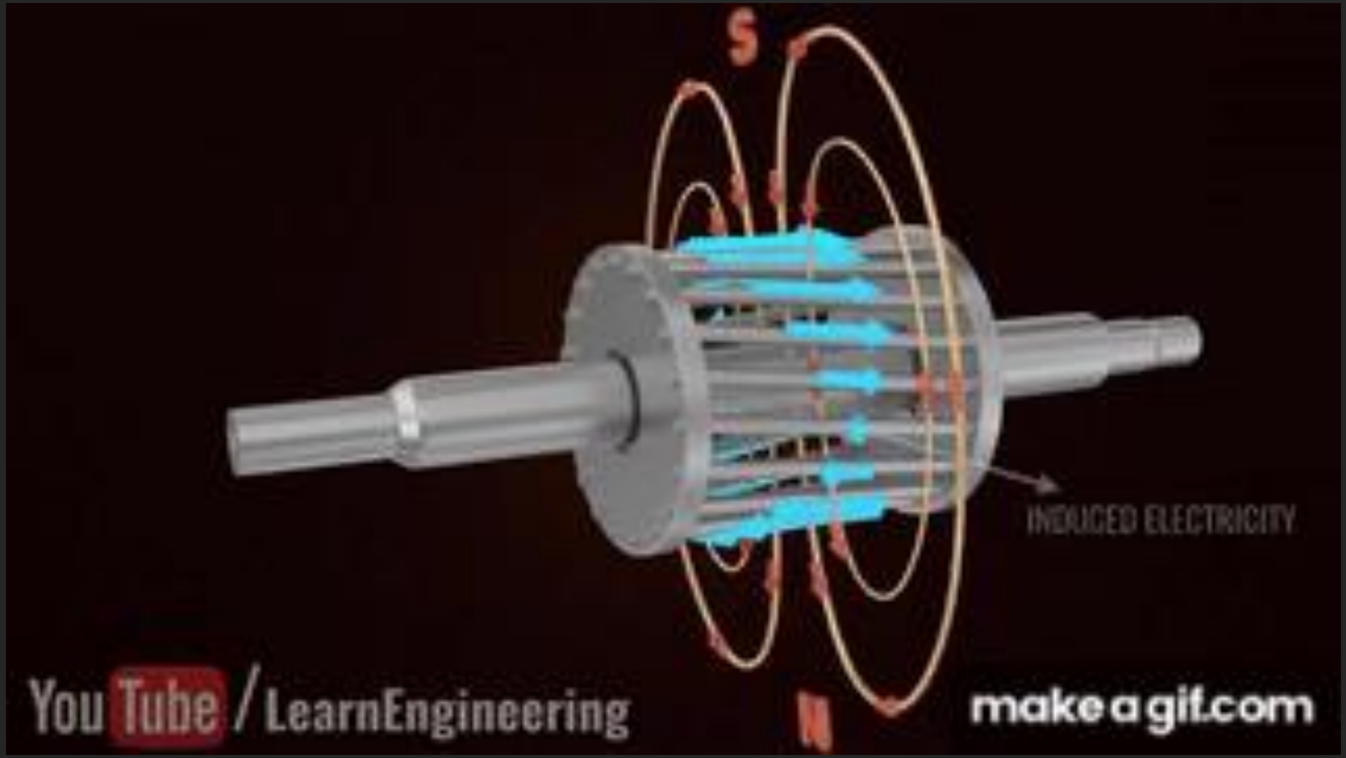
Magnetic Dipole of Wire Coil

- $\vec{\tau} = \vec{m} \times \vec{B}$
- $m = NIA$
- $\vec{\tau} = NIAB\sin(\theta)$
- $\mathrm{V} = -N\frac{\mathrm{d}\Phi}{\mathrm{d}t}$
- $\mathrm{V} = \mathrm{IR}$
- $\vec{\tau} = -\frac{N^2 IAB\sin(\theta)}{R}\frac{\mathrm{d}\Phi}{\mathrm{d}t}$



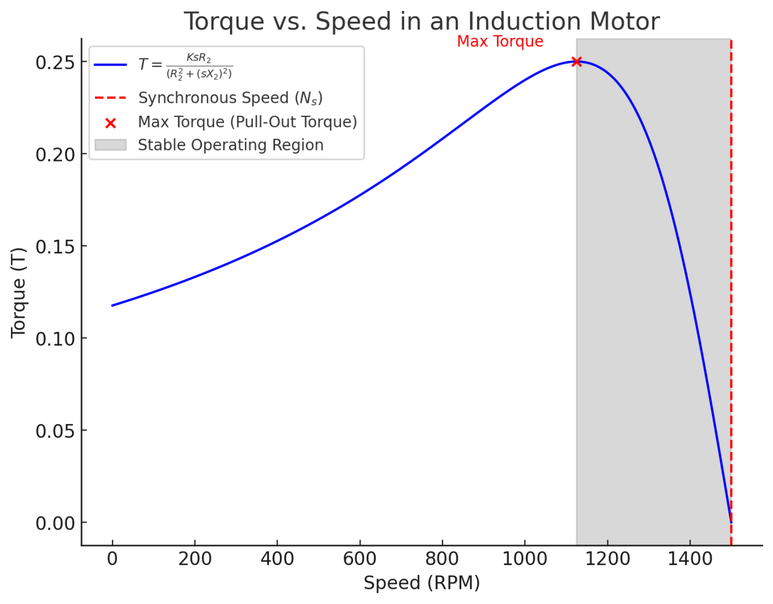
Asynchronous (Induction) AC Motors

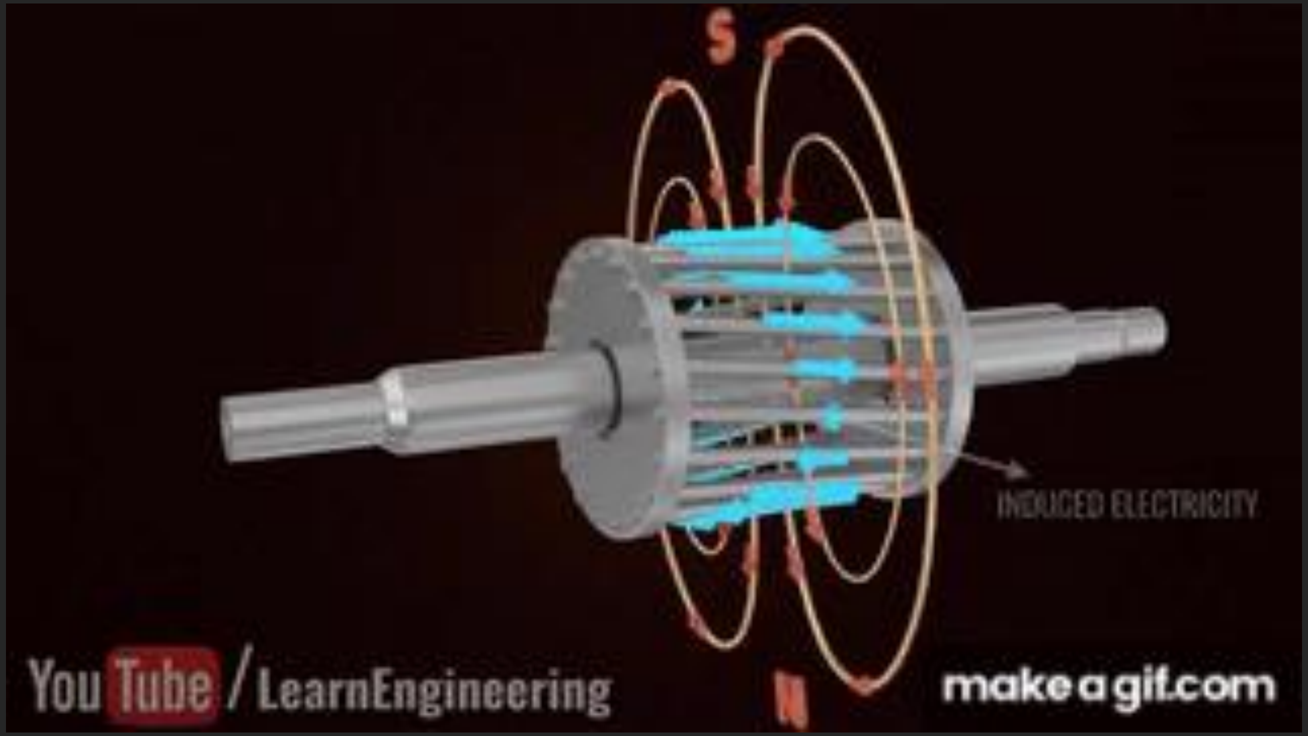




Asynchronous (Induction) AC Motors

- $s = \left(\frac{N_s - N}{N}\right)$
- $T = \frac{KsR}{R+(sX)^2}$



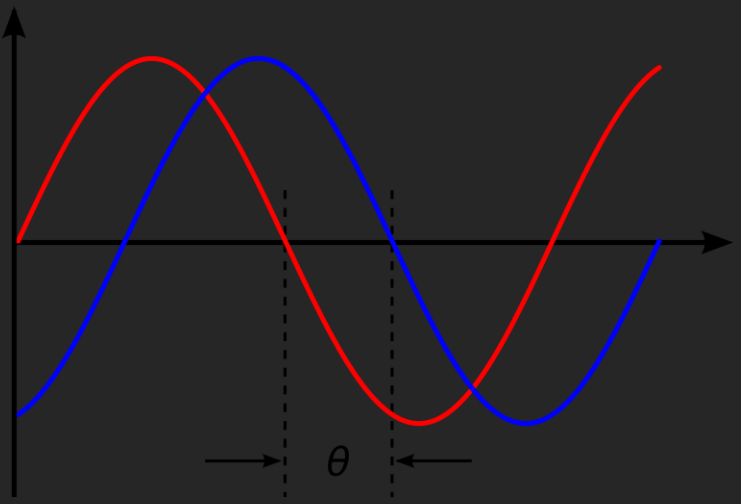


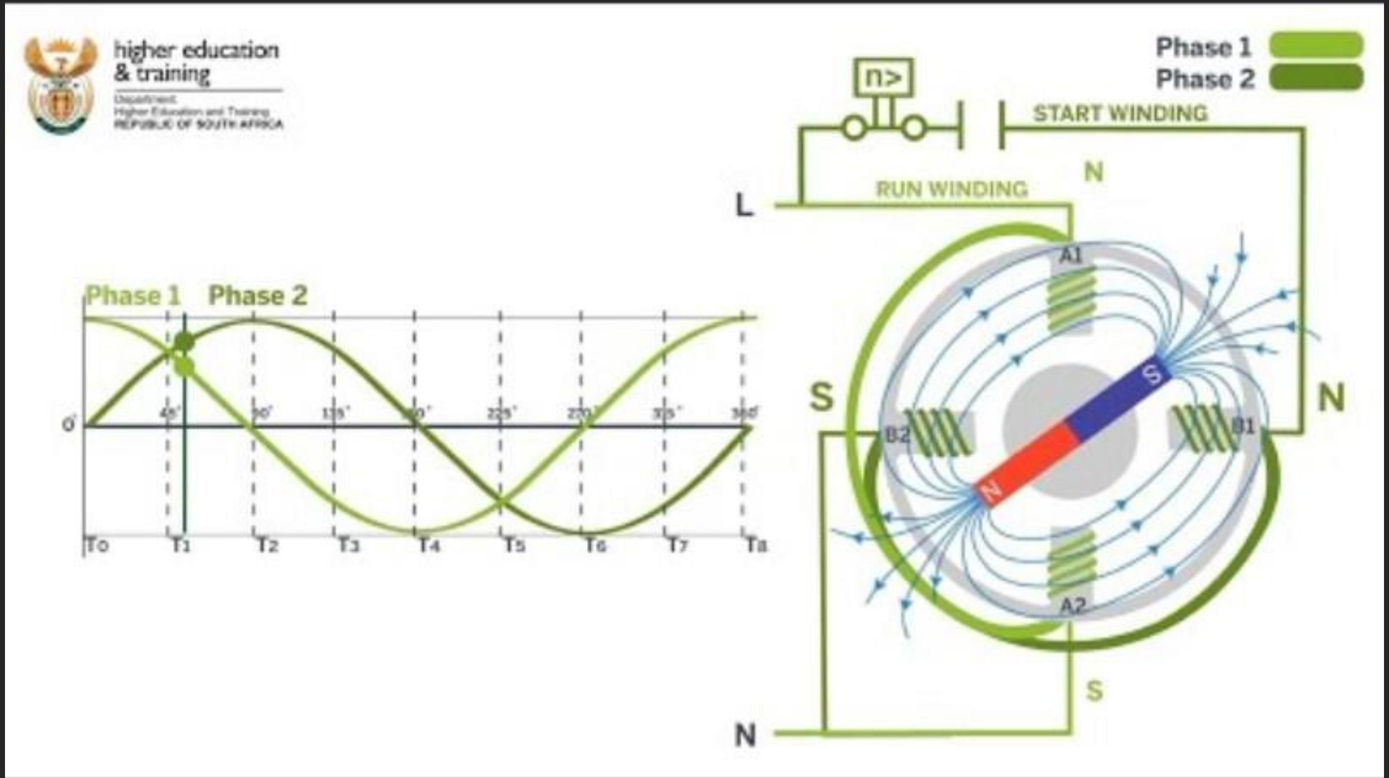
Asynchronous (Induction) AC Motors

- Advantages
  - Simple, low maintenance, low cost: no brushes, commutators, magnets
  - Robust, durable, and scalable
  - Self-starting (3-phase power)
  - Efficient for consistent loads near full speed
- Disadvantages
  - No precise speed control (without VFD)
  - Low starting torque
  - Requires 3-phase power

Single Phase Induction Motor

- $c = \frac{1}{(2\pi f)^2 L_{aux}}$





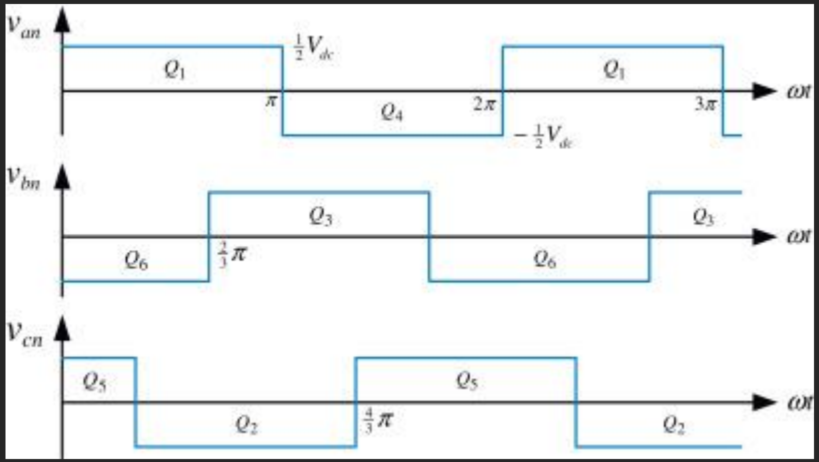
Asynchronous (Induction) AC Motors

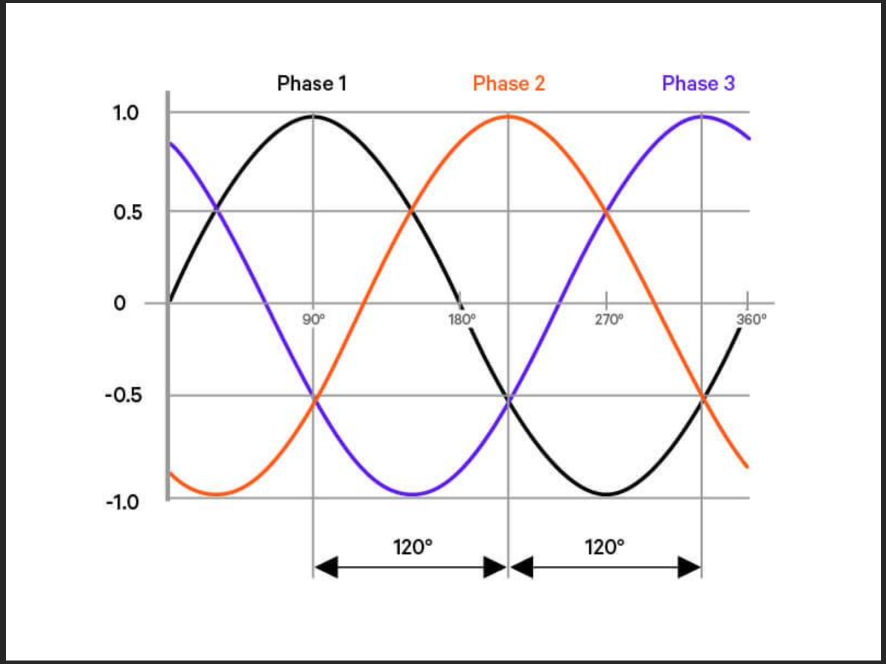
- Industrial
  - Conveyer belts, pumps, compressors, blowers
- HVAC
  - Fans, chillers, compressors
- Consumer products
  - Hairdryers, vacuums, fridge/freezer, washing machine

- Use when precise control is not necessary
- Use when cost, reliability, and robustness are important

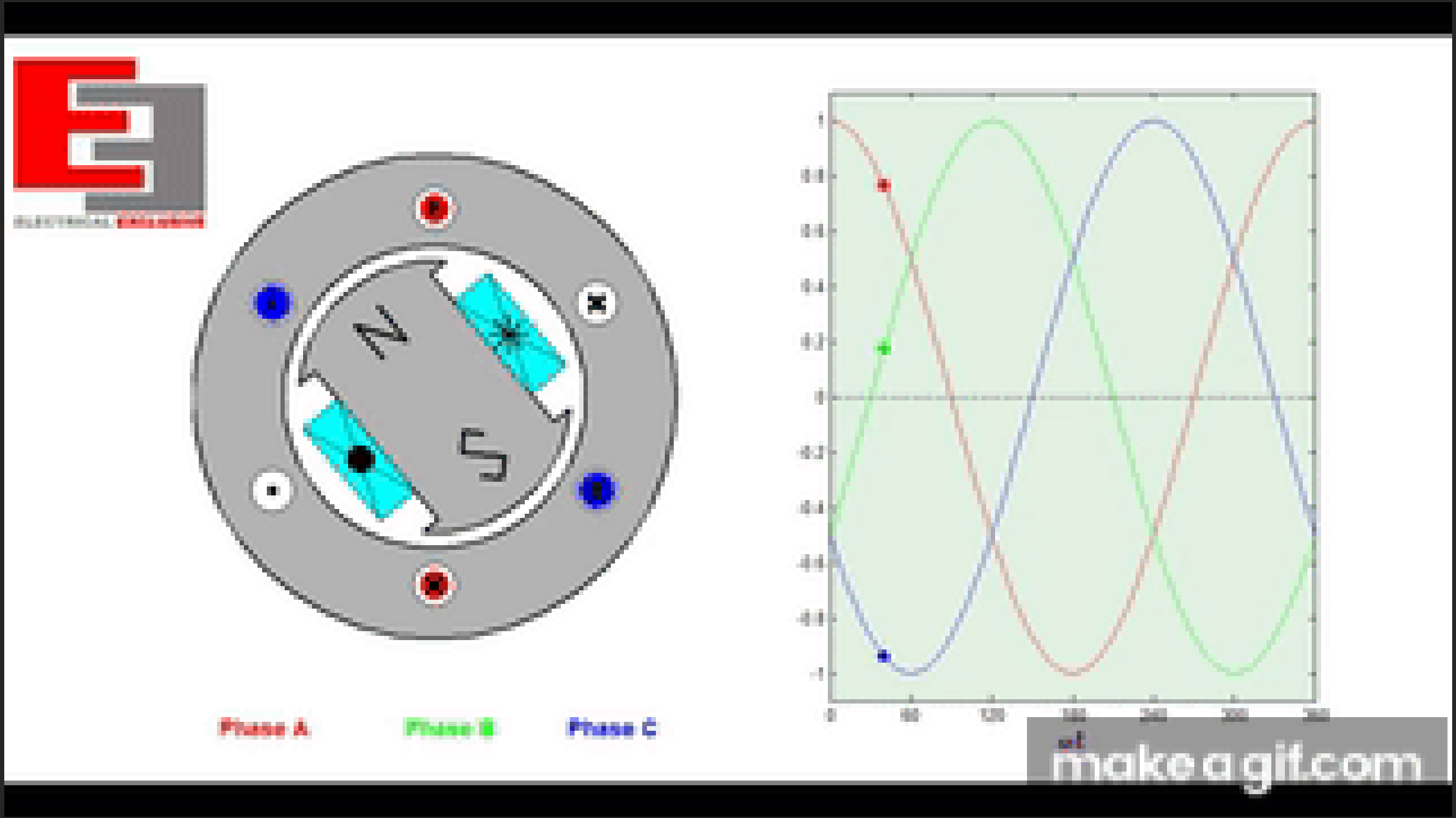
Synchronous AC Motors

- Similar to a brushless DC motor, only driven by an AC current instead of DC motor driver
- Rotor contains permanent magnets of DC current driven electromagnets





Synchronous AC Motors



Synchronous AC Motors

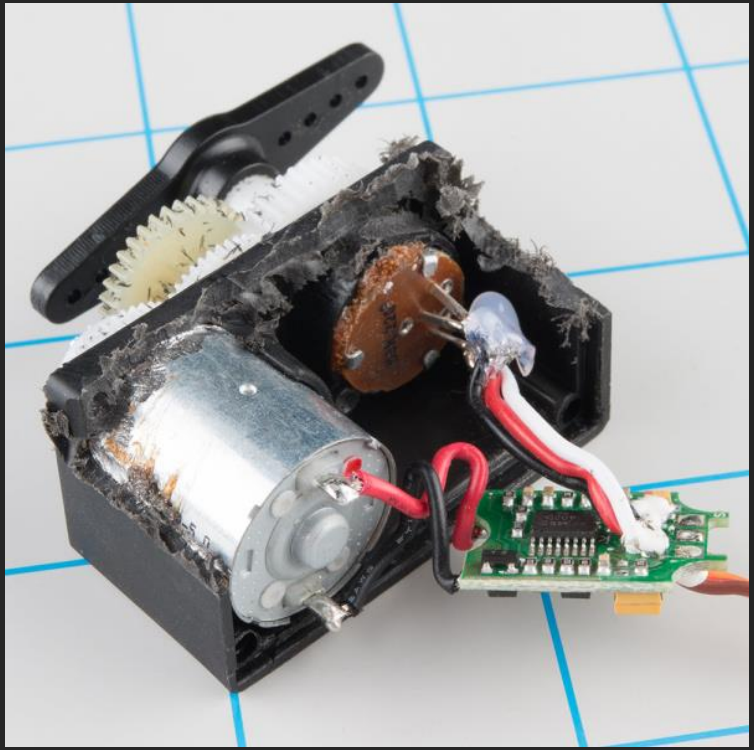
- Advantages
  - Precise speed control
  - Very efficient
  - High torque density
- Disadvantages
  - Not self starting
  - Requires VFD for speed control
  - Sensitive to load disturbances

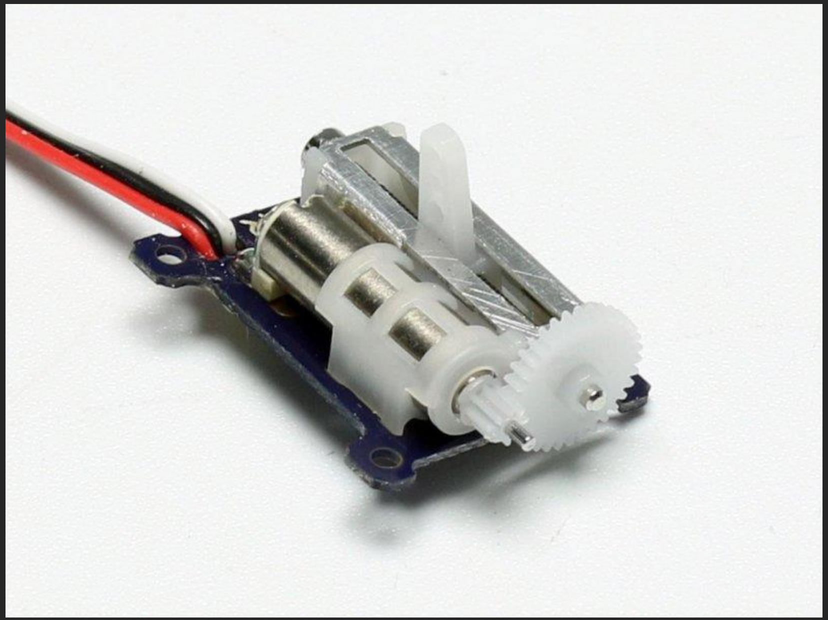
Synchronous AC Motors

- Transportation
  - Electric vehicles
- HVAC and Building Automation
  - Variable Speed compressors
- Smart Grid
  - Wind turbines and hydroelectric generators
  - Reactive power compensation

Servos

- Used for precise control of angular or linear position
- Components
  - Motor
  - Gears
  - Controller
  - Sensor
  - Feedback loop





Servos

- Positional Servo
  - Rotates within fixed range
- Continuous Rotation Servo
  - Like a DC motor but with speed and position control
- Linear Servo
  - Designed for linear position control
- Brushless Servo
  - Precise, durable, efficient servo

Servos

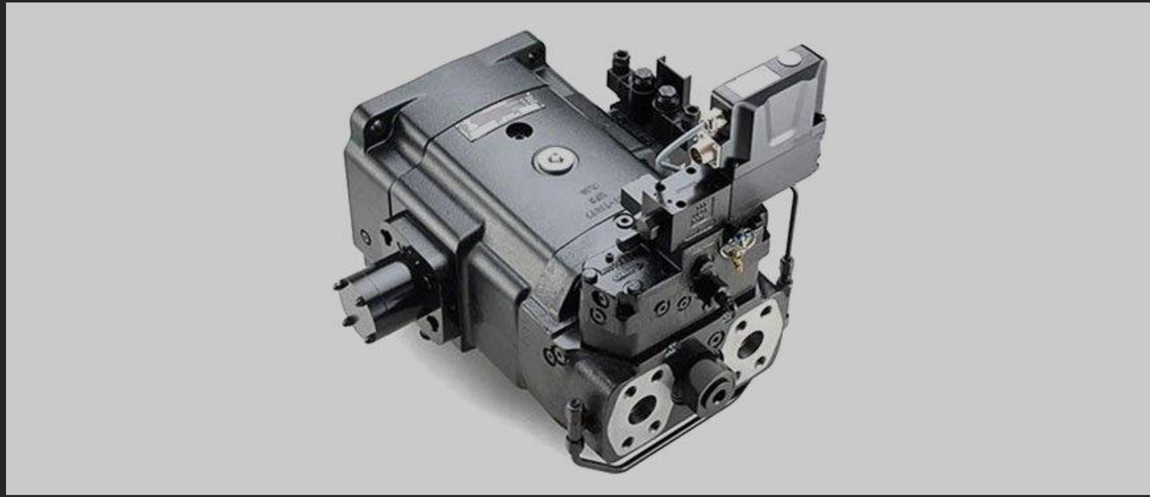
- Advantages of Servos
  - High accuracy and resolution
  - Closed-loop feedback control
  - Fast dynamic response
- Disadvantages
  - More expensive than open-loop motors
  - Requires tuning (e.g., PID parameters)
  - More complex electronics and setup

Servos

- Robotics: Joint control in robotic arms and legs
- 3D Printers & CNC Machines: High-precision tool head positioning
- Autonomous Vehicles: Steering, throttle control, camera stabilization
- Medical Devices: Prosthetics, surgical robots, drug dispensing
- Smart Manufacturing: Conveyor sorters, automated arms, inspection systems
- Aerospace & Defense: Missile fins, gimbal tracking, satellite actuators
- Precision Agriculture: Spray nozzles, robotic planters, soil probes

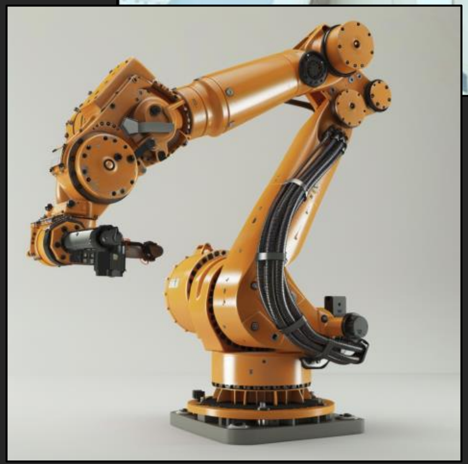
Hydrostatic Actuation

- Fluid Transmission: hydraulic pump pressurizes fluid and transmits through tubes
- Actuator Response: Pressurized fluid exerts force on piston or motor
- Control: Valves open/close to control movement, force, and speed



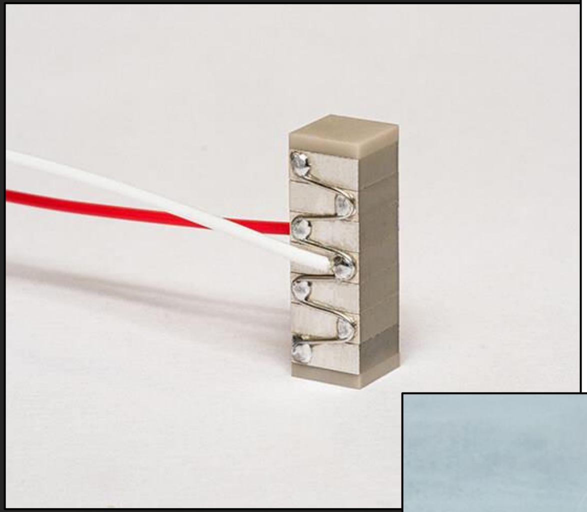
Hydrostatic Actuation

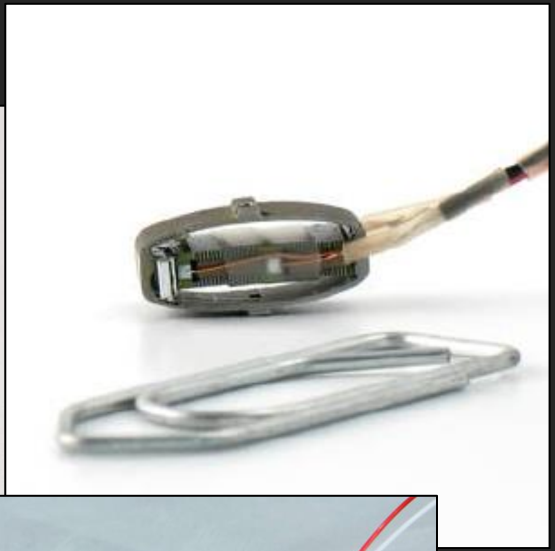
- Advantages of Hydrostatic Actuation
  - High Force Generation
  - Smooth and Precise Control
  - Load-Holding Capability
- Disadvantages of Hydrostatic Actuation
  - Complexity and Maintenance
  - Potential for Leaks
  - Limited Speed for Lightweight Applications

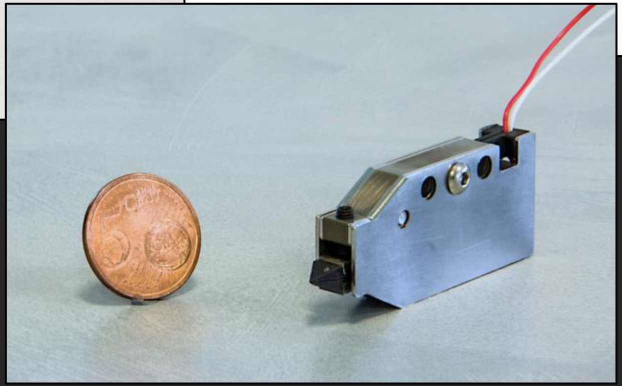


Piezoelectric Actuator

- Piezoelectric Effect: Certain materials generate mechanical strain when exposed to an electric field
- Advantages
  - High Precision
  - Fast Response Time
  - Minimal Mechanical Parts
  - Quiet Operation
- Disadvantages
  - Limited Range of Motion
  - High Voltage Requirement
  - Temperature Sensitivity

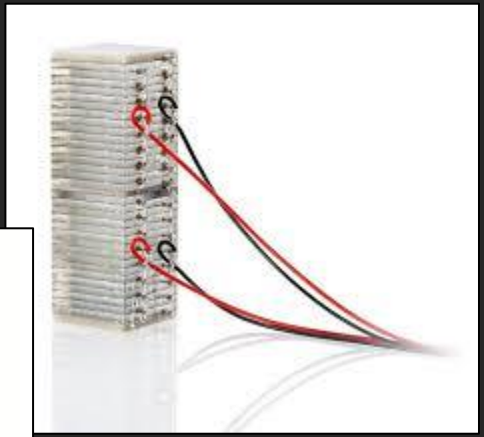
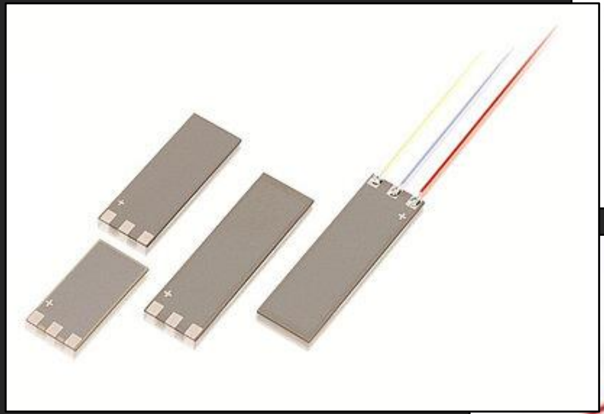
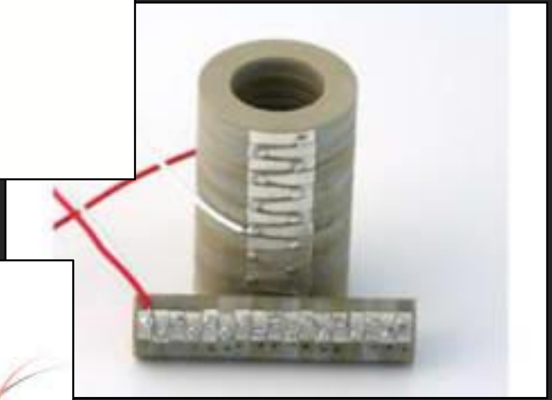
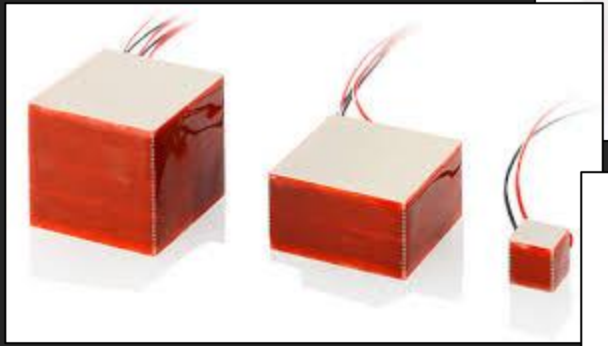
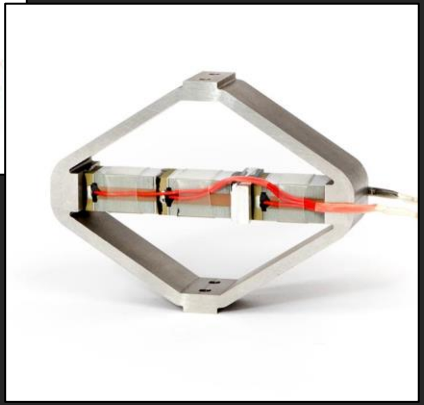






Piezoelectric Actuator

- Stacked
  - High force, limited movement
- Bending
  - Larger displacement, lower force
- Tube
  - Radial and longitudinal displacement
- Shear
  - Lateral movement
- Amplified

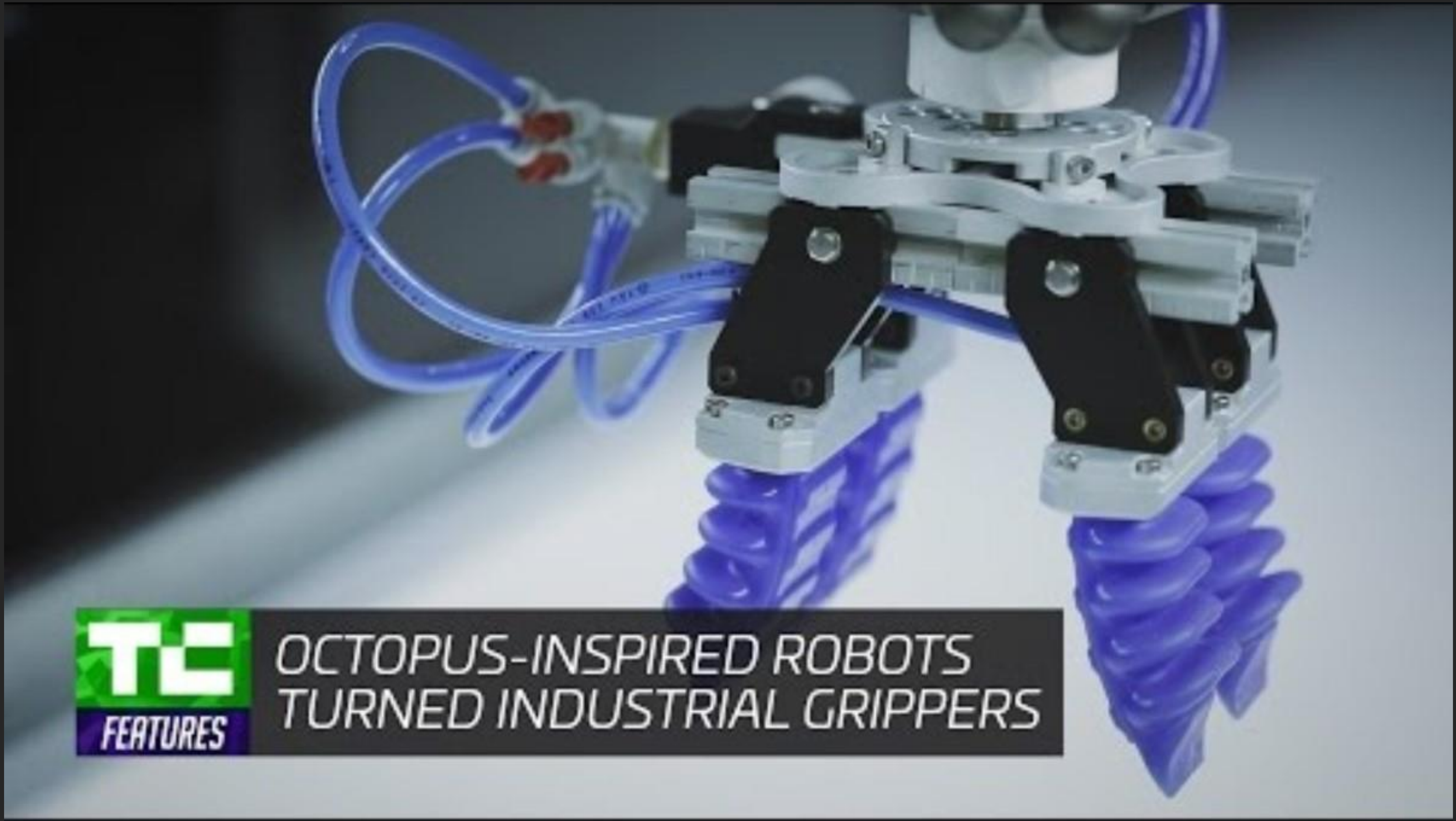






Pneumatic Actuators

- Compressed Air: Pneumatic actuators are powered by compressed air, typically generated by a compressor
- Linear Actuators (Pneumatic Cylinders):
  - Single-Acting Cylinder: Air is applied on one side of the piston, and a spring or exhaust port returns it to its original position
  - Double-Acting Cylinder: Air is applied alternately to both sides of the piston, allowing push-and-pull
- Rotary Actuators:
  - Convert compressed air into rotary or circular motion

Pneumatic Actuators

- Advantages of Pneumatic Actuators
  - Fast Response and High Speed
  - Simple and Cost-Effective
  - High Force-to-Weight Ratio
- Disadvantages of Pneumatic Actuators
  - Limited Precision
  - Air Compressibility
  - Continuous Supply Required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FEATURES
OCTOPUS-INSPIRED ROBOTS
TURNED INDUSTRIAL GRIPPERS

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Harnessing non-uniform pressure distributions in soft robotic actuators

In submission with Advanced Intelligent Systems, Oct 2022