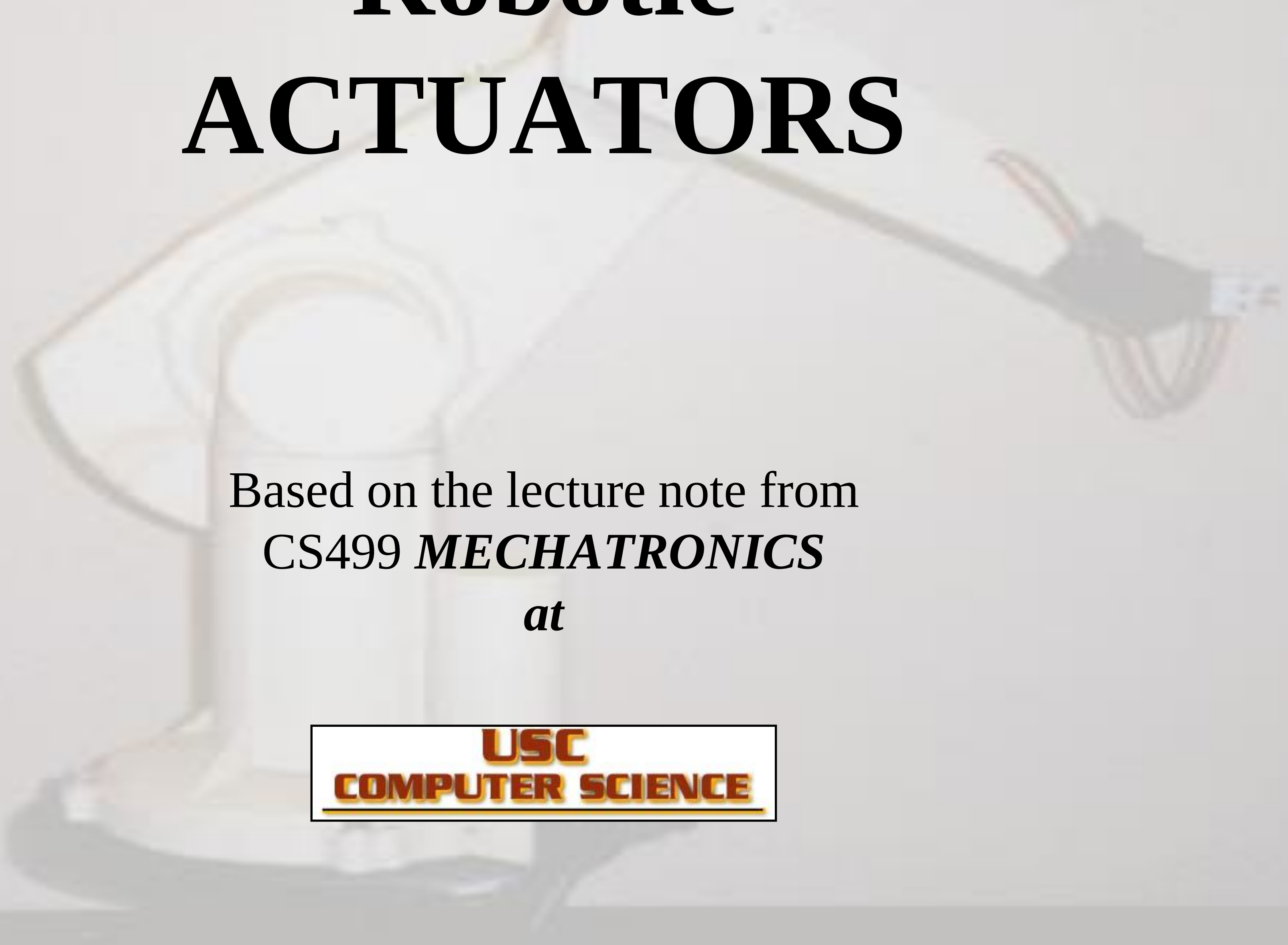
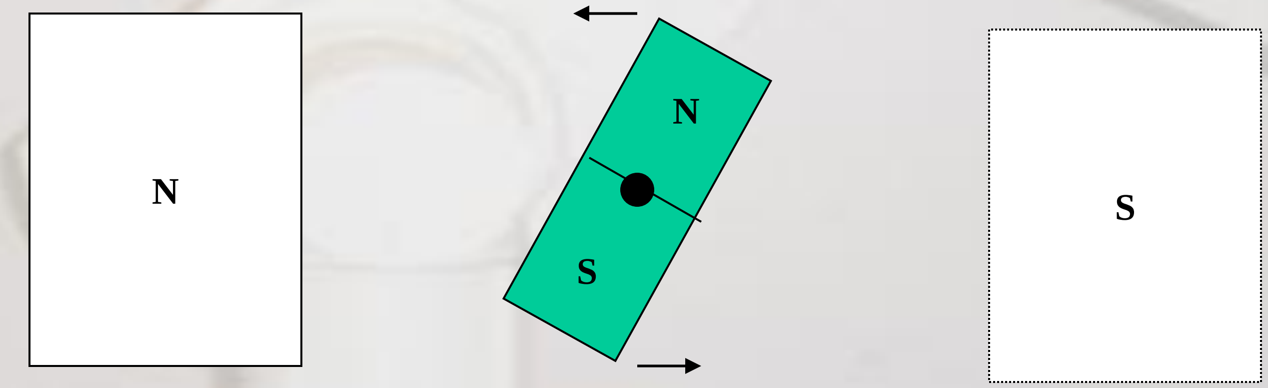


Robotic ACTUATORS

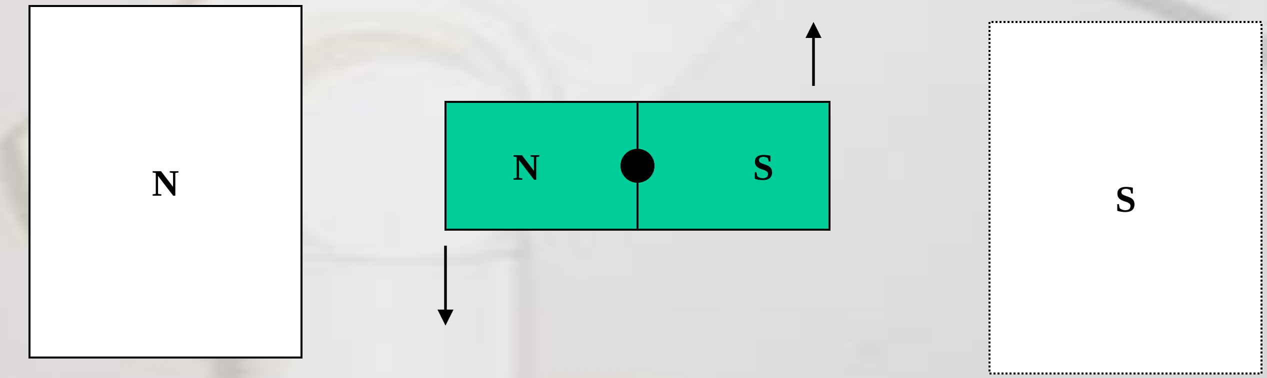
Based on the lecture note from
CS499 ***MECHATRONICS***
at

USC
COMPUTER SCIENCE

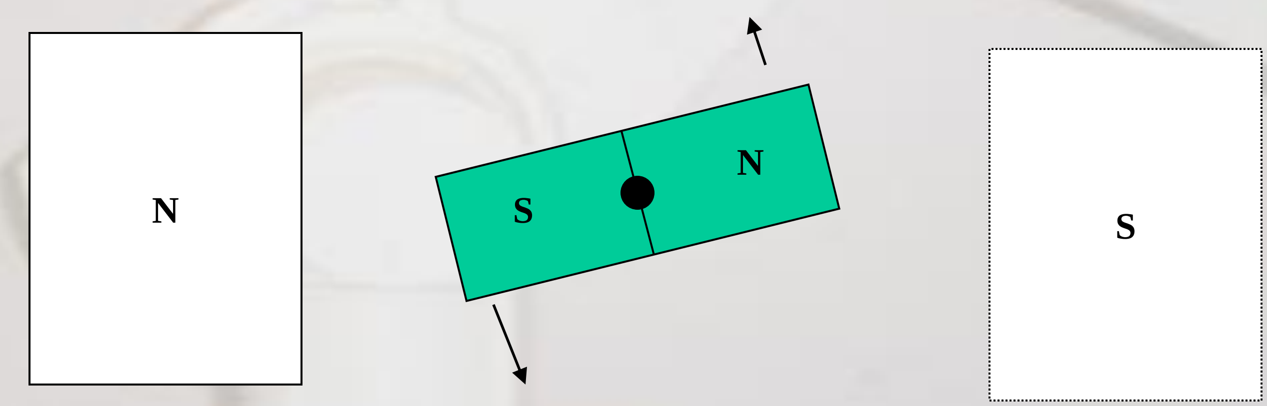
Motors: Key Concepts



Motors: Key Concepts

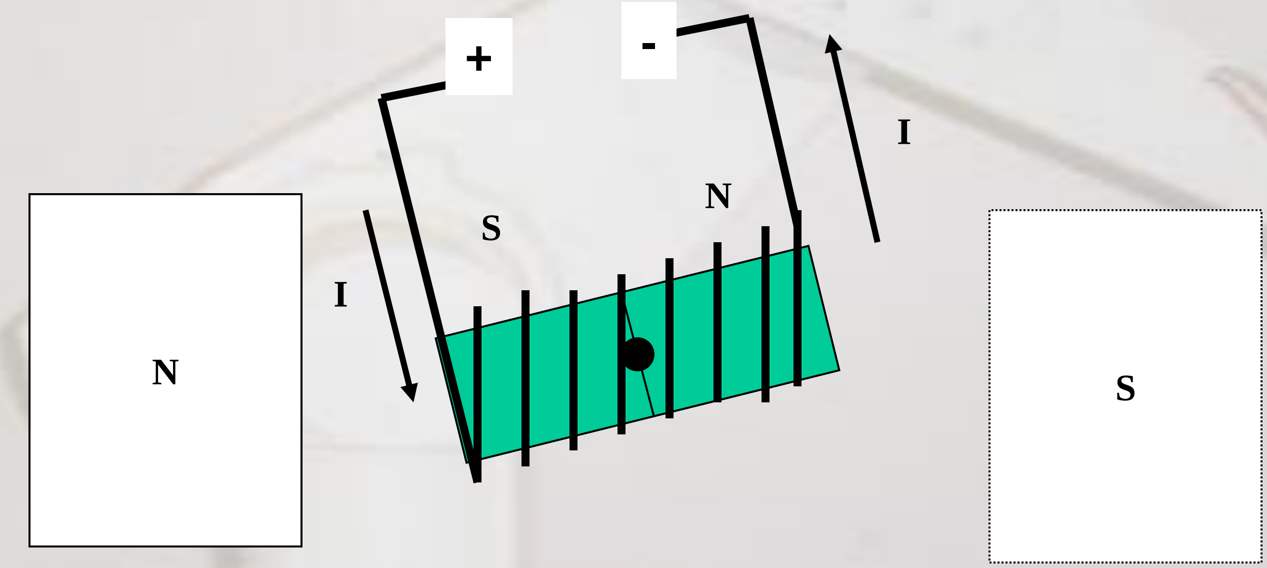


Motors: Key Concepts

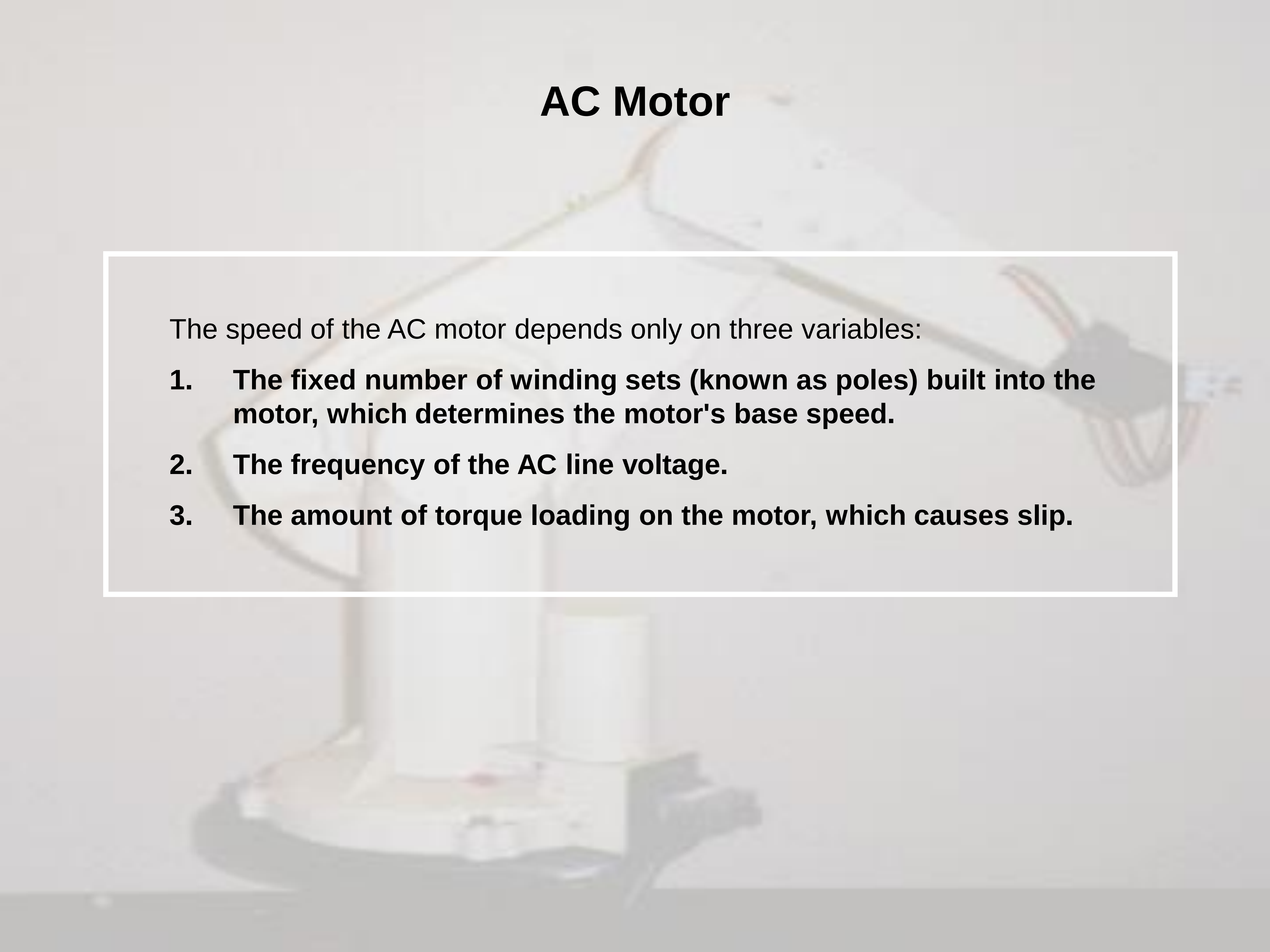


Motors: Key Concepts

AC inverts the poles



AC Motor



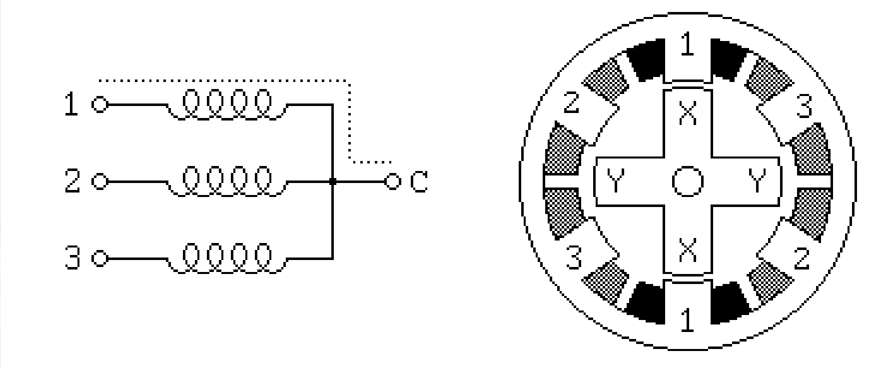
The speed of the AC motor depends only on three variables:

1. **The fixed number of winding sets (known as poles) built into the motor, which determines the motor's base speed.**
2. **The frequency of the AC line voltage.**
3. **The amount of torque loading on the motor, which causes slip.**

Motor: Key Concepts

- In the simplest three-phase motor, there are 3 separate electromagnets formed by the single set of three-way windings.
- The windings are in the exterior (stator) section.
- The changing field in the windings causes the rotor to rotate around the axis of the motor.

Stepping Motors

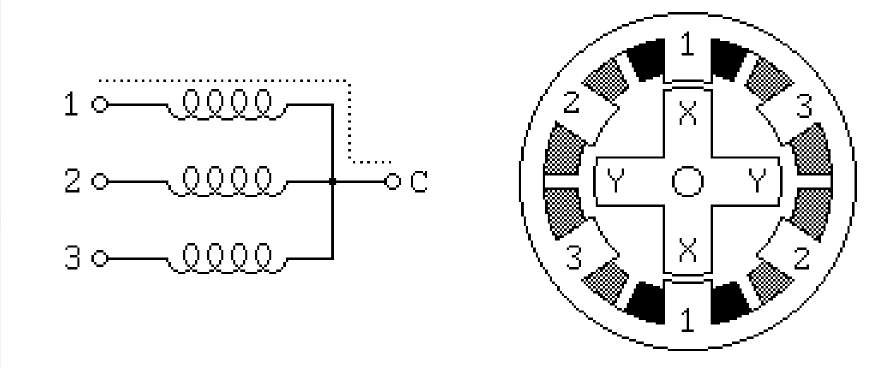


Basic Speed:

As the three voltage phases (each 120 degrees off from one another) gradually rise and fall, the strength of each electromagnetic winding set rises and falls in relation to the frequency of the voltage changes.

This causes the rotor to rotate once per voltage cycle. In a 60 Hertz system, this results in a base speed of 60 Hertz, or 3600 rpm.

Stepping Motors



- To rotate the motor continuously, power must be applied to the 3 windings in sequence.

- The following control sequence will spin the motor clockwise for 2 revolutions: (1 means turning on the current through a motor winding).

Winding 1: 1001001001001001001001001
Winding 2: 0100100100100100100100100
Winding 3: 0010010010010010010010010
time --->

Stepping Motors

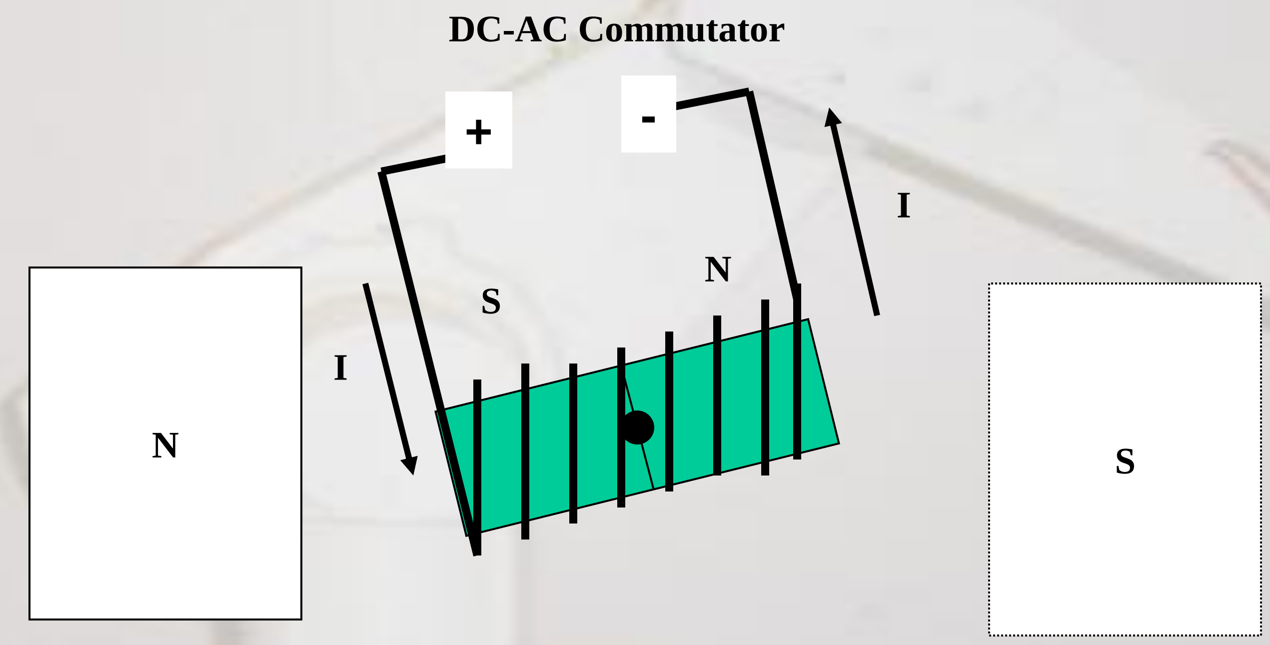
Stepper motors have more than 2 terminals, up to 6 and 8,

which activate sequentially each coil within the motor.

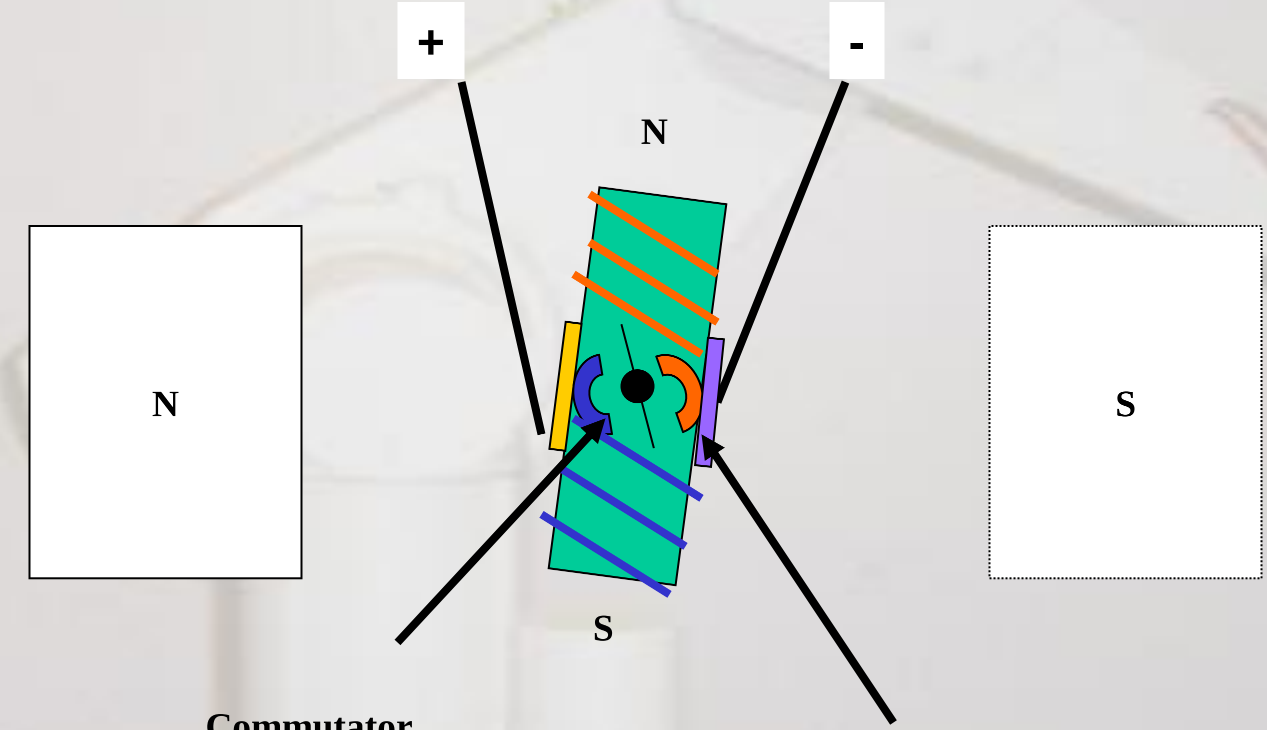
- The timing of the signal determines the motor’s speed.
- The phase between the signal determines the direction.
- The number of commands determines the position

- Stepping motors come in a wide range of angular resolutions.
- The coarsest motors typically turn 90 degrees per step, while high resolution permanent magnet motors are commonly able to handle 1.8 or even 0.72 degrees per step

Motors: Key Concepts



Brush-type DC Motors: Key Concepts



+

-

N

N

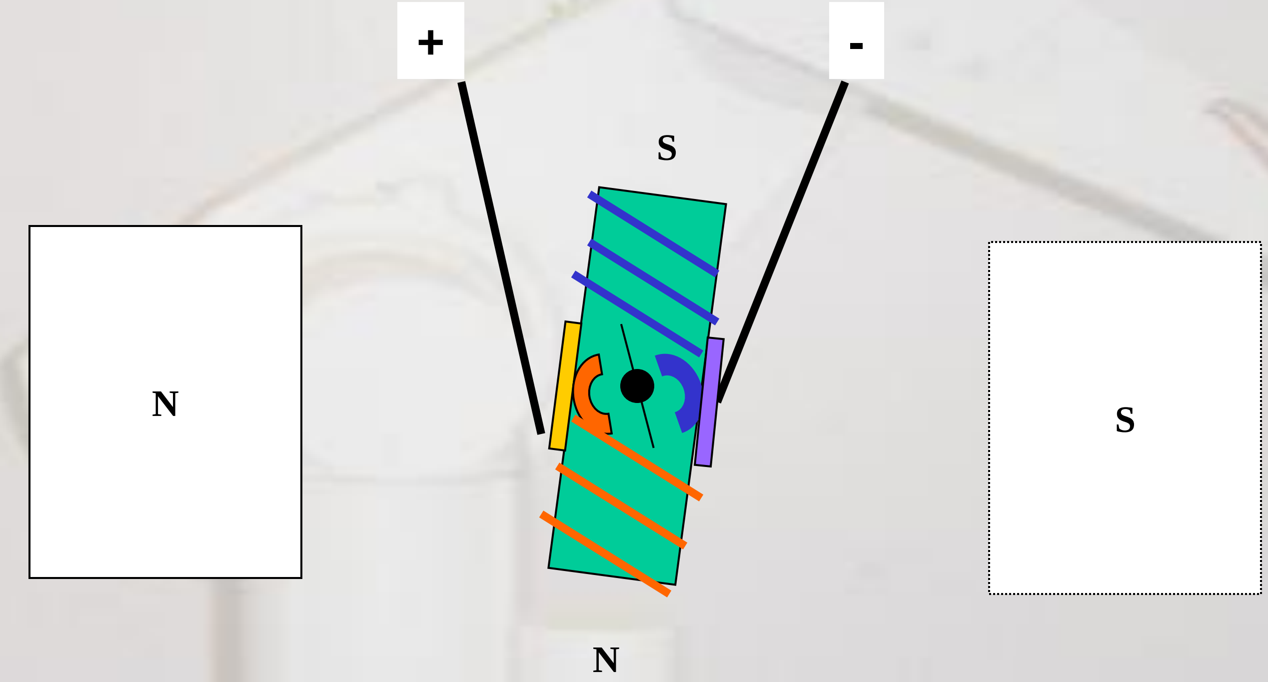
S

S

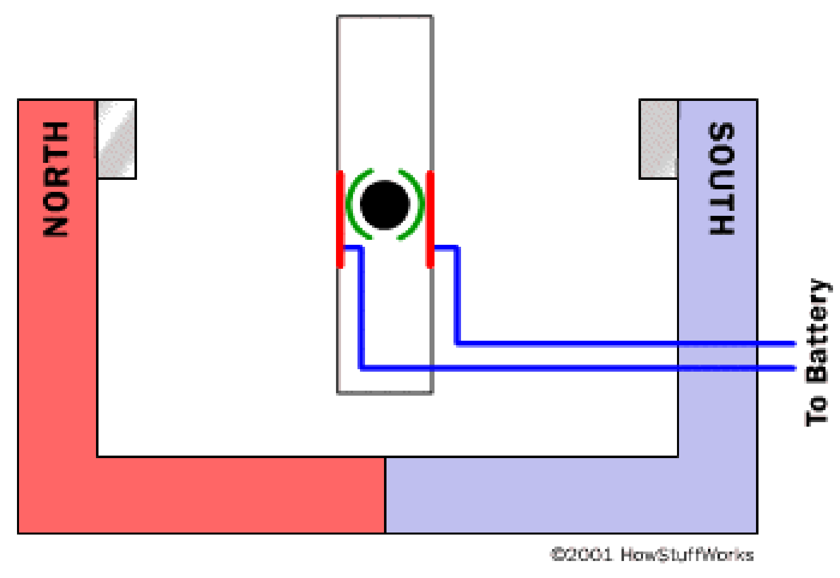
Commutator

Brushes

Brush-type DC Motors: Key Concepts



Brush-type DC Motors: Key Concepts



DC Motors: Basic Principle

Brush-like and Brushless DC Motors

Brush-like

- To allow the rotor to turn without twisting the wires, the ends of the wire loop are connected to a set of contacts called the ***commutator***, which rubs against a set of conductors called the ***brushes***.
- The brushes make electrical contact with the commutator as it spins, and are connected to the positive and negative leads of the power source, allowing electricity to flow through the loop.
- The electricity flowing through the loop creates a magnetic field that interacts with the magnetic field of the permanent magnet to make the loop spin.

Brushless:

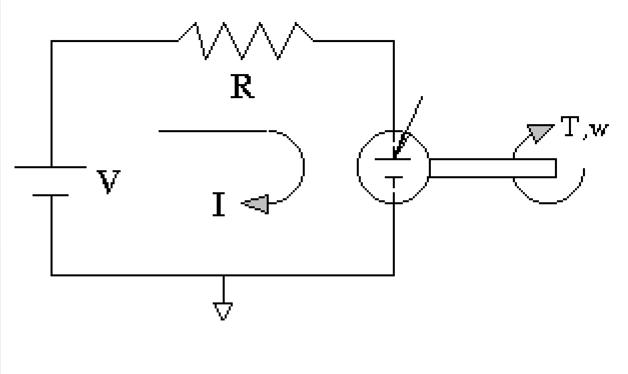
- DC current is converted into AC current, using position sensors and microcontroller.

Elementary Theory of DC Permanent Magnet Motors

A motor transforms Electrical Energy into Mechanical Energy.

Electrical Power $P_e = V \cdot I$

Mechanical Power $P_m = T \cdot \omega$



$$P_e = \eta \cdot P_m$$

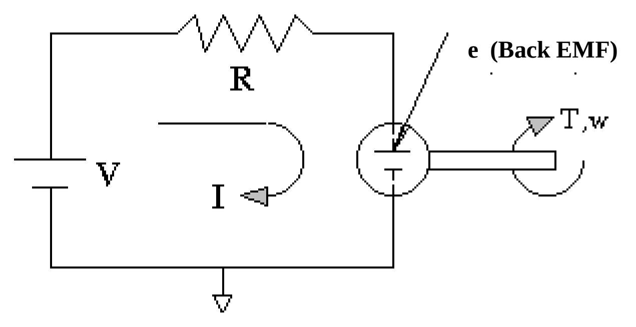
Elementary Theory of DC Permanent Magnet Motors

When the motor rotates, the variation of current induces a voltage across the motor winding.

E (back Electromagnetic Force)

Kirchoff's voltage law

$$\boxed{V = I \cdot R + e}$$



Stall current
Motor stopped, e=0

$$\boxed{I_s = \frac{V}{R}}$$

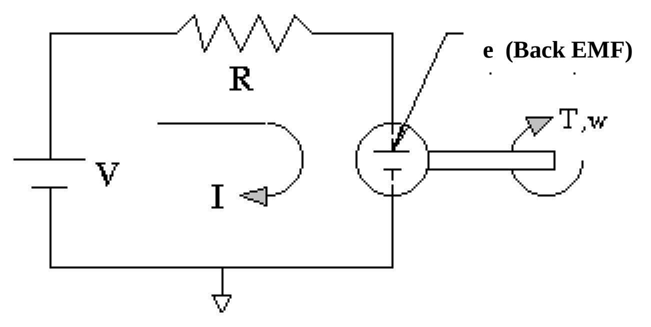
Elementary Theory of DC Permanent Magnet Motors

Conservation of Energy:

Electrical energy input = mechanical work output +
electromagnetic stored energy +
heat loss

$$P_e = \eta \cdot P_m$$

$$P_e = P_m + I \cdot R^2$$



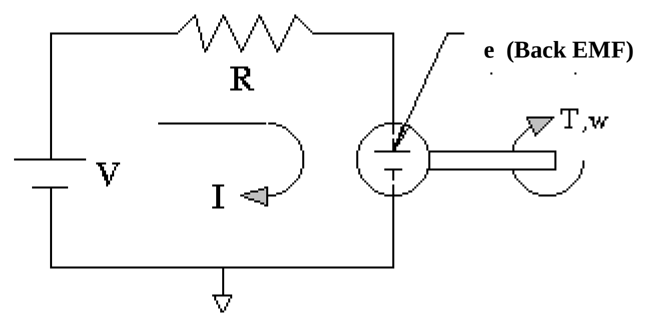
Elementary Theory of DC Permanent Magnet Motors

When the rotor is turning, e increases prop. to the speed.

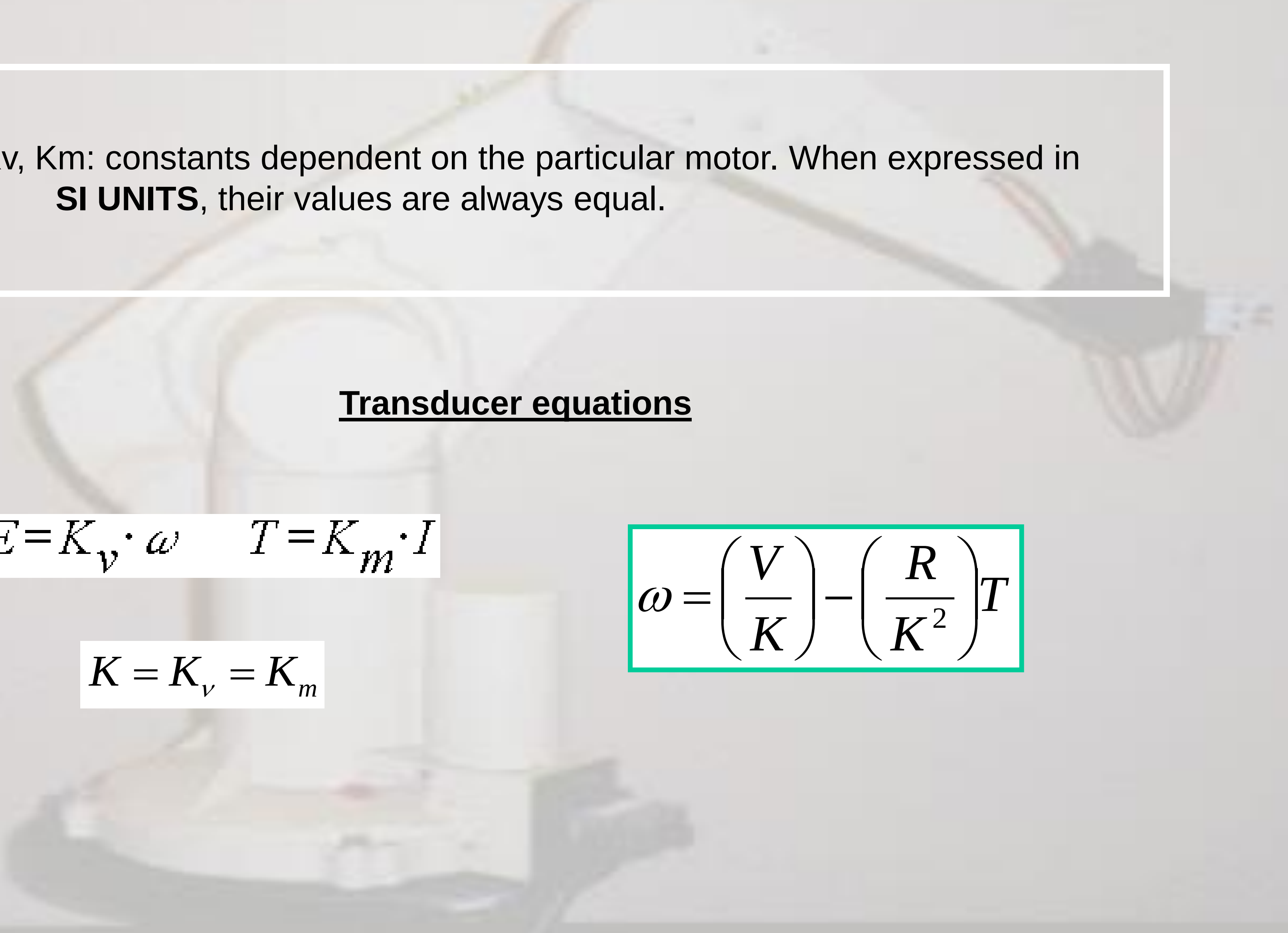
The torque produced by the motor depends on the flux around the loop of the conductor, which is controlled by the current.

$$e = k_e \cdot \omega$$

$$T = k_t \cdot I$$



Elementary Theory of DC Permanent Magnet Motors



Kv, Km: constants dependent on the particular motor. When expressed in **SI UNITS**, their values are always equal.

Transducer equations

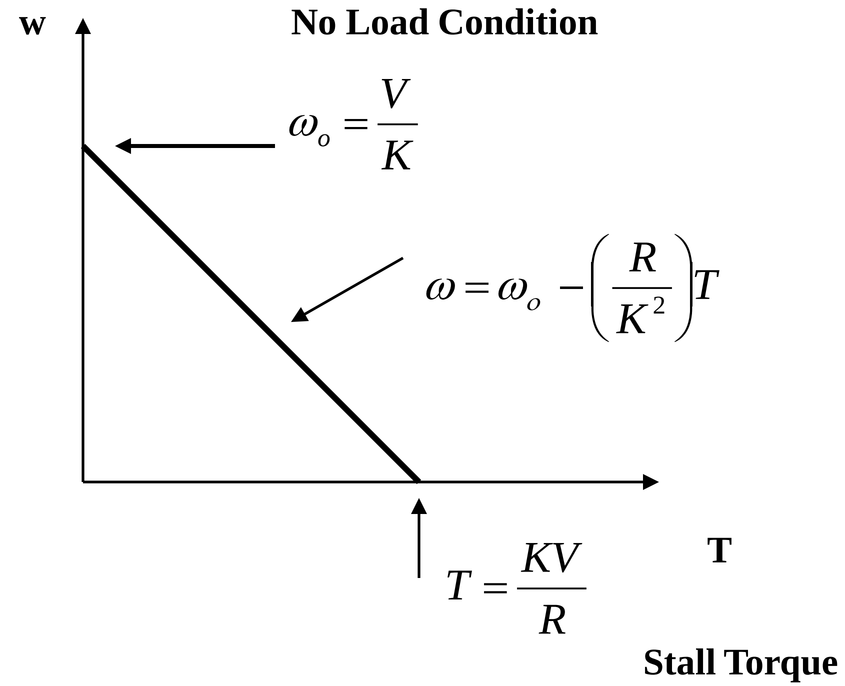
$$E = K_v \cdot \omega \qquad T = K_m \cdot I$$

$$\omega = \left(\frac{V}{K}\right) - \left(\frac{R}{K^2}\right) T$$

$$K = K_v = K_m$$

Elementary Theory of DC Permanent Magnet Motors

The speed is inversely proportional to the torque.



No Load Condition

$$\omega_o = \frac{V}{K}$$

$$\omega = \omega_o - \left(\frac{R}{K^2}\right)T$$

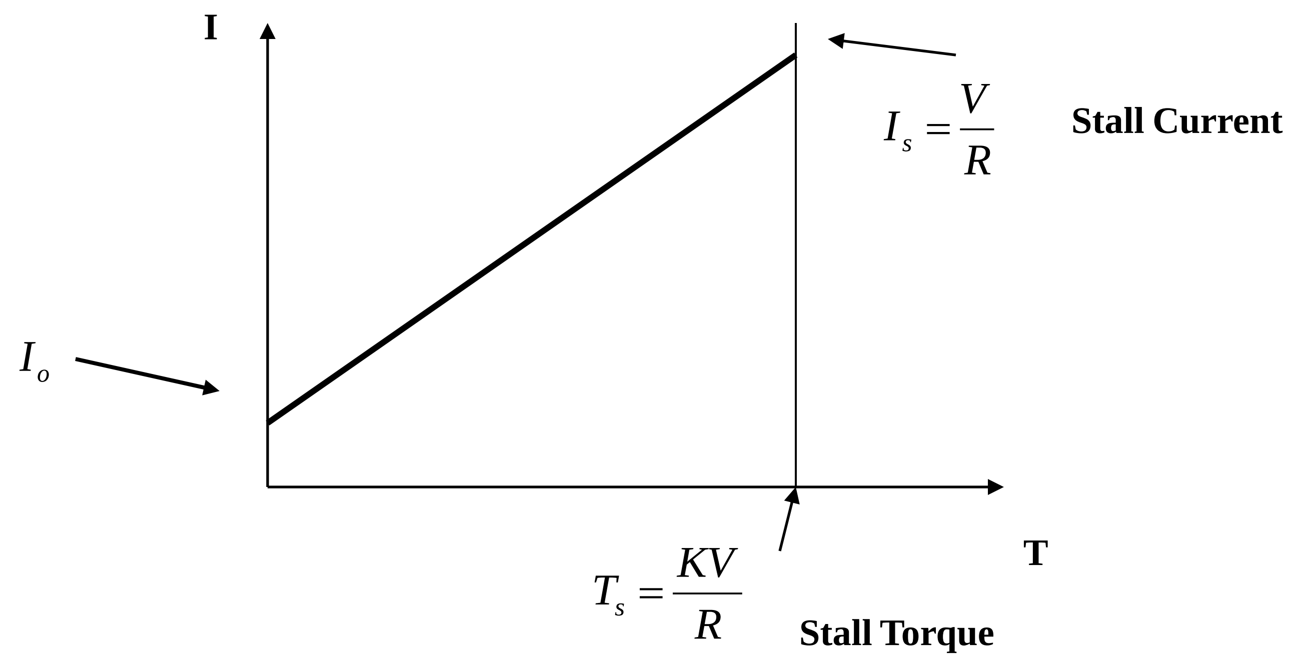
$$T = \frac{KV}{R}$$

Stall Torque

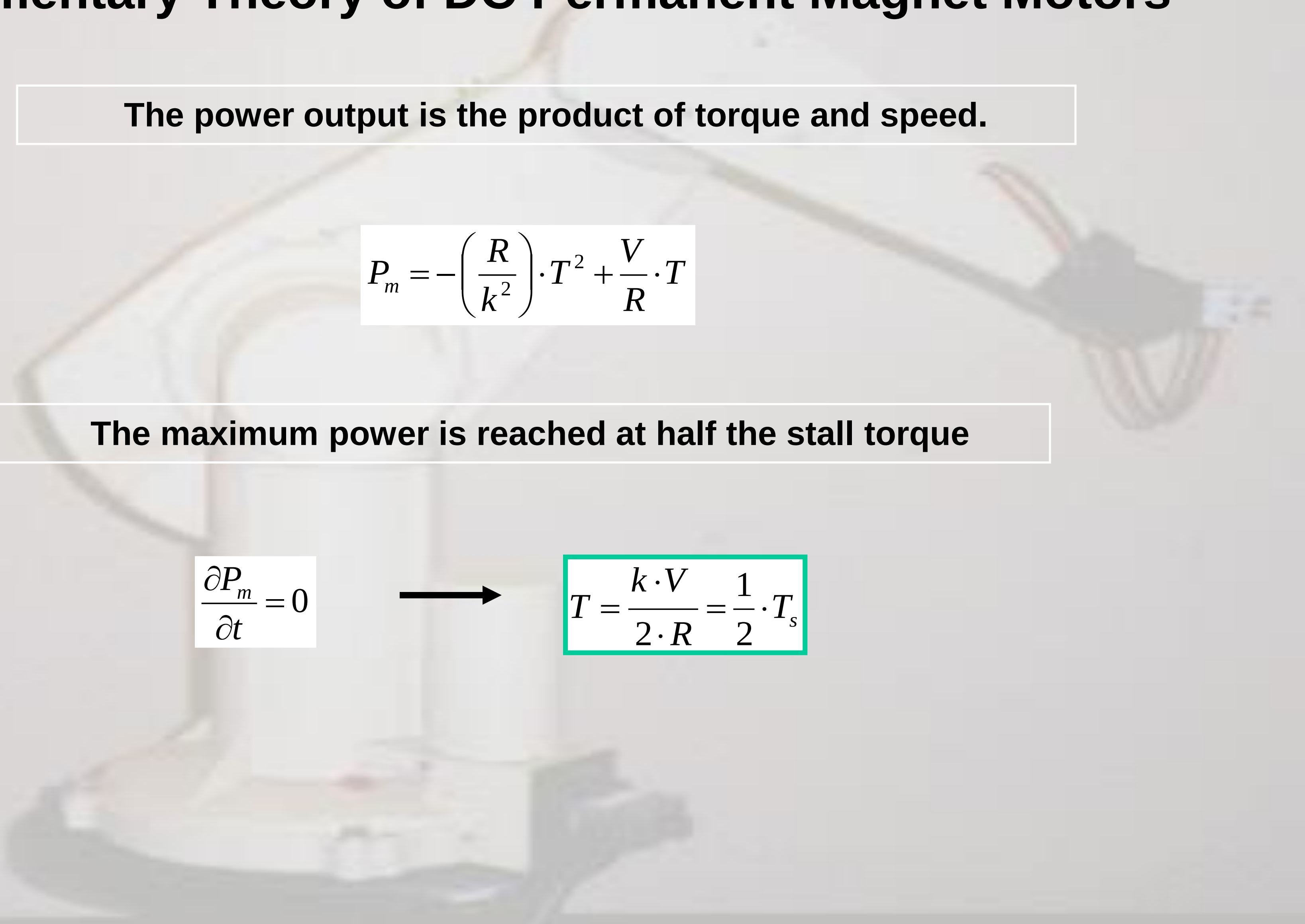
Elementary Theory of DC Permanent Magnet Motors

The current is proportional to the torque.

The stall current is the maximal current that the motor can pump.



Elementary Theory of DC Permanent Magnet Motors



The power output is the product of torque and speed.

$$P_m = -\left(\frac{R}{k^2}\right)\cdot T^2 + \frac{V}{R}\cdot T$$

The maximum power is reached at half the stall torque

$$\frac{\partial P_m}{\partial t} = 0 \quad \longrightarrow \quad \boxed{T = \frac{k\cdot V}{2\cdot R} = \frac{1}{2}\cdot T_s}$$

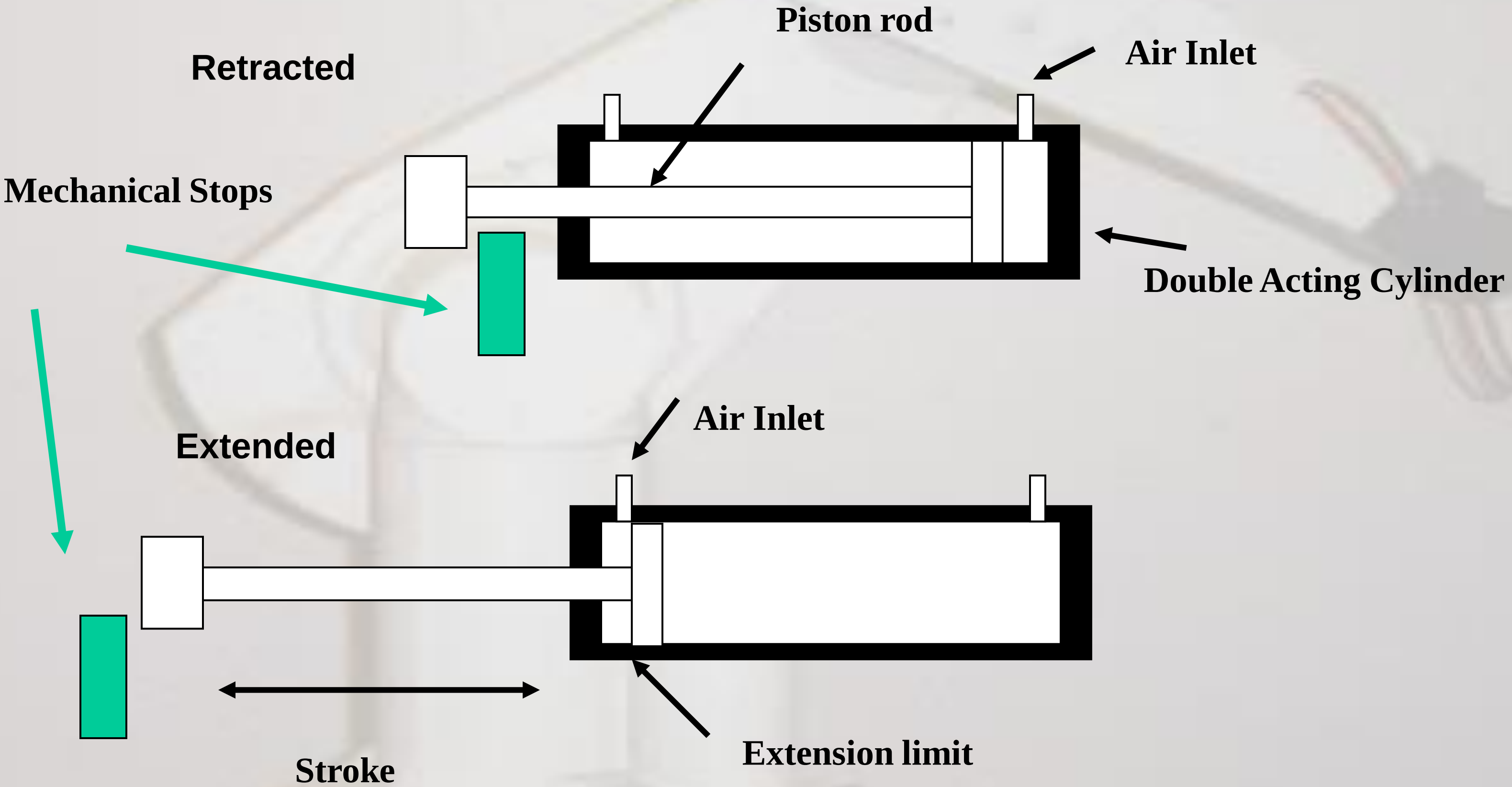
Elementary Theory of DC Permanent Magnet Motors

The point of maximum efficiency is a low torque, high-speed operating point.

Therefore, it is good to take an oversized motor so that it can run at the maximum of efficiency.

$$\boxed{\eta_{\max} = \left(1 - \sqrt{\frac{I_0}{I_s}}\right)^2}$$

Hydraulic and Pneumatic Motors



Retracted

Piston rod

Air Inlet

Mechanical Stops

Double Acting Cylinder

Extended

Air Inlet

Stroke

Extension limit

Hydraulic and Pneumatic Motors

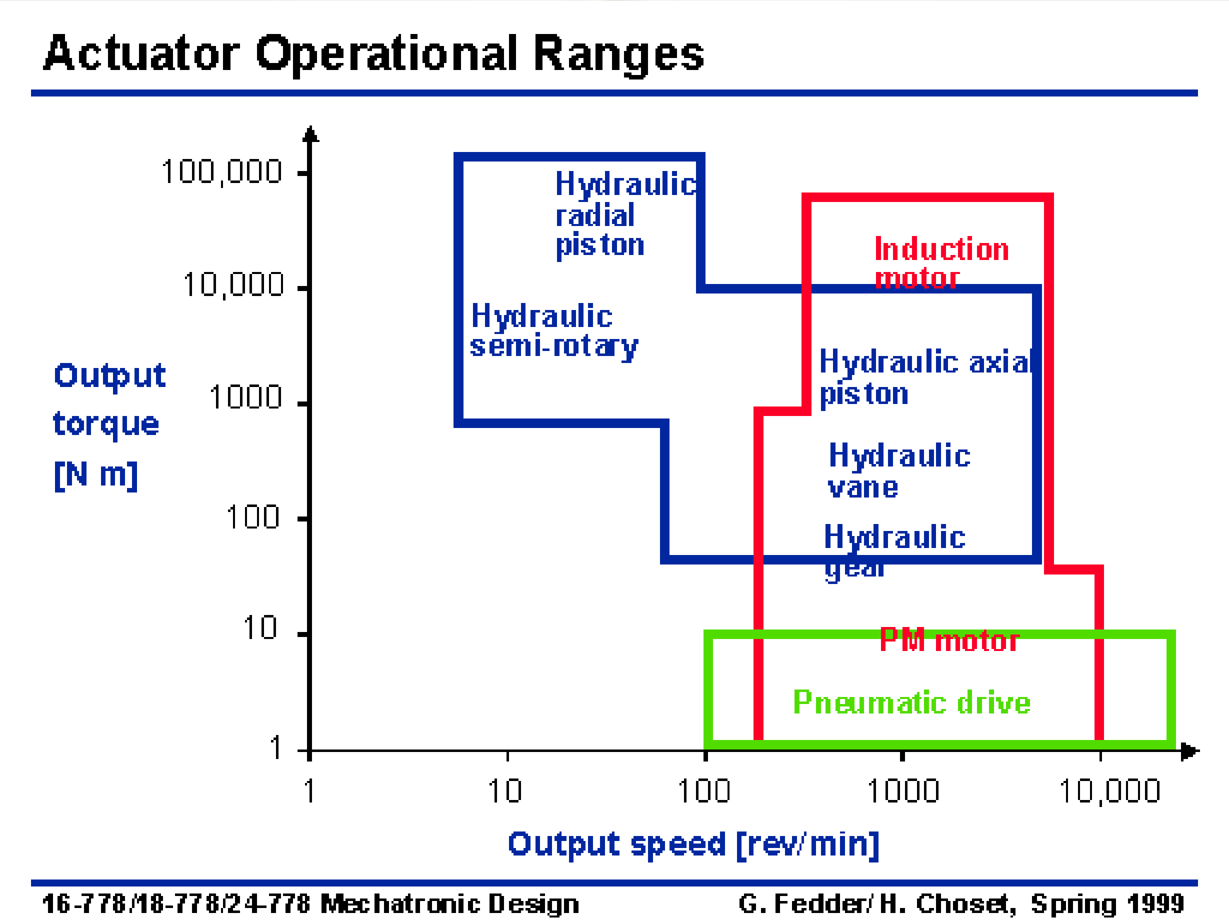
Pneumatic Power - Air-powered cylinders

- **Compressed air**
- **Either stored on board or injected by a pump**
- **Produces linear motion through activation of cylinders**

Hydraulic Power - Fluid (non-air)-powered cylinders

- **Uncompressible fluid, most often oil.**
- **Requires a pump to generate the pressure and flow rate needed.**
- **Complex and difficult to build effectively, and costly.**

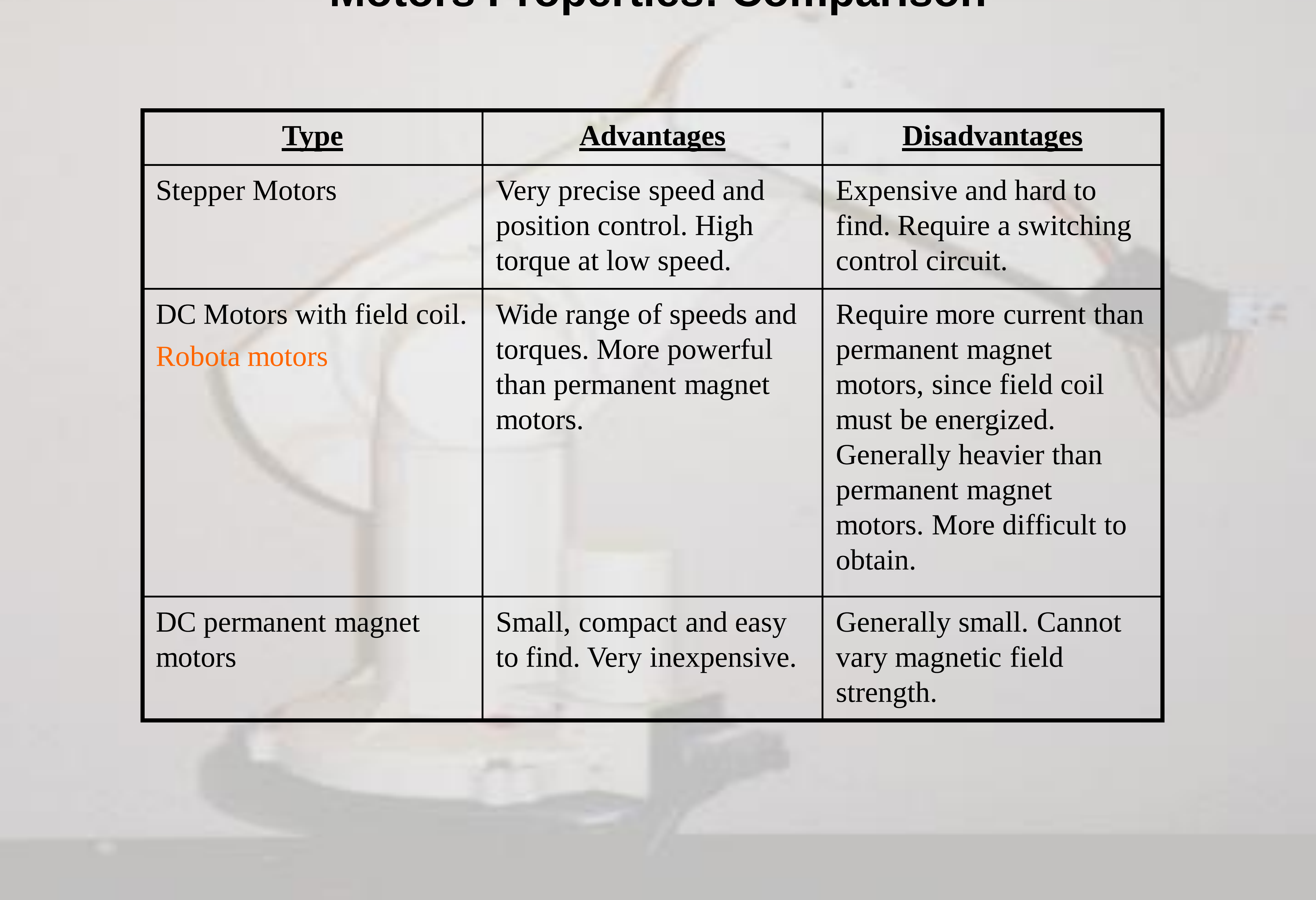
Motors Properties: Comparison



Actuator Operational Ranges

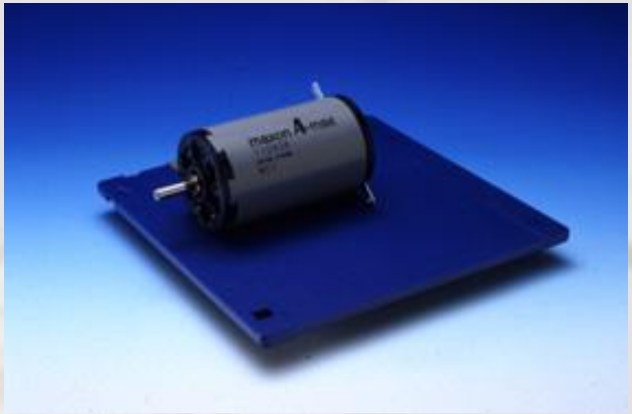
16-778/18-778/24-778 Mechatronic Design G. Fedder/ H. Choset, Spring 1999

Motors Properties: Comparison



Type	**Advantages**	**Disadvantages**
Stepper Motors	Very precise speed and position control. High torque at low speed.	Expensive and hard to find. Require a switching control circuit.
DC Motors with field coil. Robota motors	Wide range of speeds and torques. More powerful than permanent magnet motors.	Require more current than permanent magnet motors, since field coil must be energized. Generally heavier than permanent magnet motors. More difficult to obtain.
DC permanent magnet motors	Small, compact and easy to find. Very inexpensive.	Generally small. Cannot vary magnetic field strength.

Robota motors

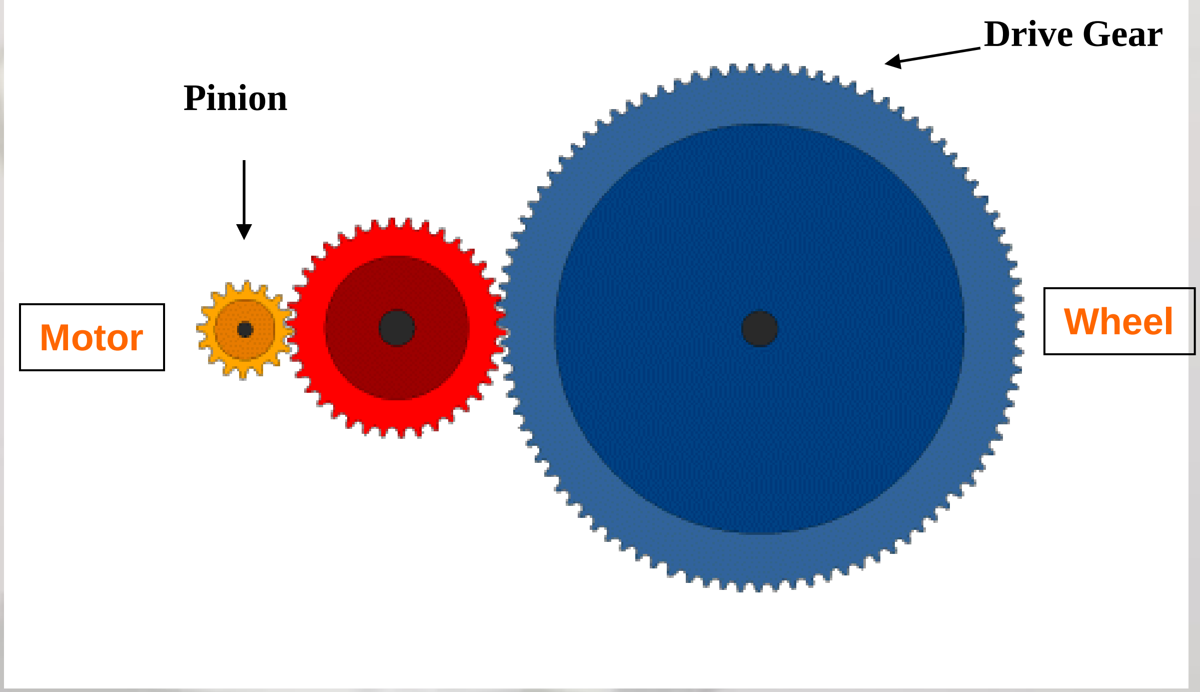


- **Maxon A-max 26 mm**
- Rhombic moving coil design provides long life, low electrical noise, fast acceleration and high efficiency.
- The ironless rotor allows zero cogging and simple accurate control. Available with either precious metal brushes or graphite brushes the power rating ranges from 4 to 11 watts.
- The motor length is 44.7 mm (1.76 in) and weighs in at 106 g (3.73 oz).
- Maximum efficiency: 86%.
- Maximum continuous torque from the motor alone is up to 15.5 mNm (2.19 oz-in)
- Matching gearheads available with ratios ranging from 4.3:1 to 2548:1 capable of delivering 4500 mNm (637 oz-in) of continuous torque.
- Matching encoders are also available.

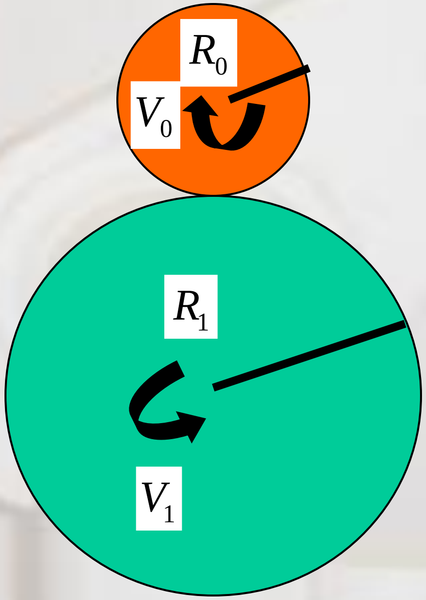
Gears: Types, Ratio and Use

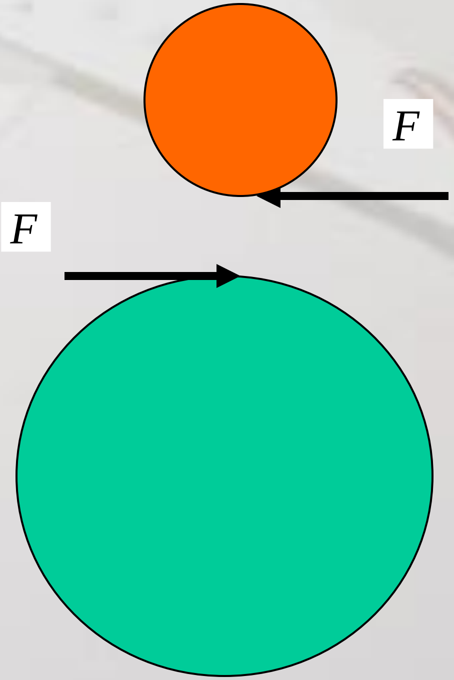
Gears: Basics

DC motors usually run at too high a speed or too low a torque for controlling a small robot. Thus, a DC must be geared down.



Calculating Gear Ratios



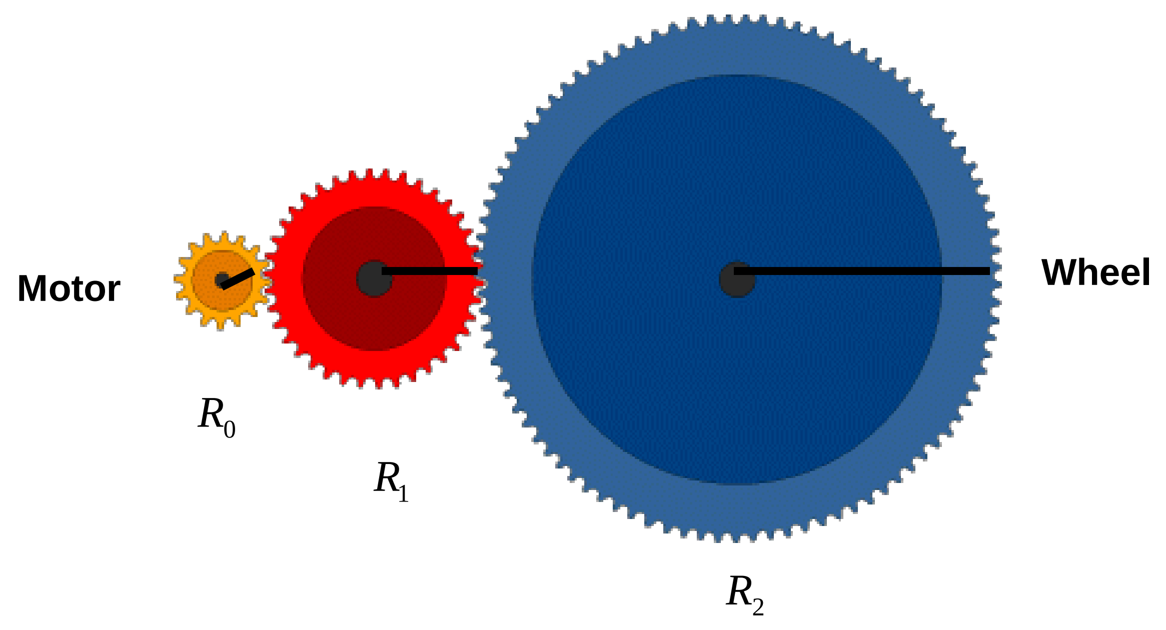


$$F \cdot R_o = T_0$$

$$F \cdot R_1 = T_1$$

$$\Rightarrow \quad \frac{T_1}{T_0} = \frac{R_1}{R_0} \quad \Rightarrow \quad \frac{V_1}{V_0} = \frac{R_0}{R_1}$$

Calculating Gears Ratios for a Gear Train



$$\frac{T_2}{T_0} = \frac{R_2}{R_0}$$

$$\frac{V_2}{V_0} = \frac{R_0}{R_2}$$

Gear Train: ratio 1:6

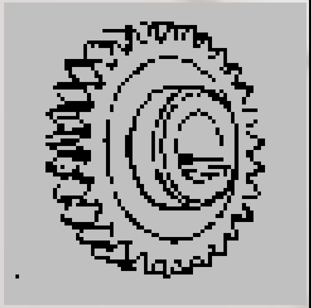
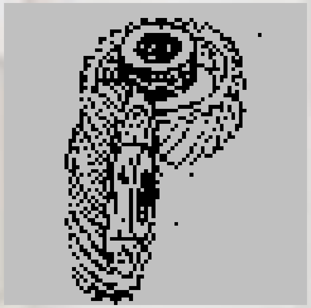
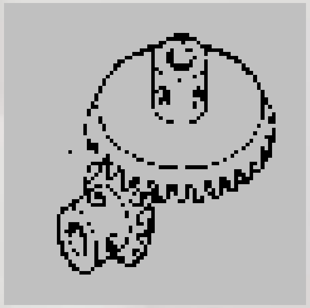
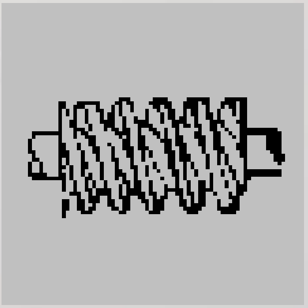
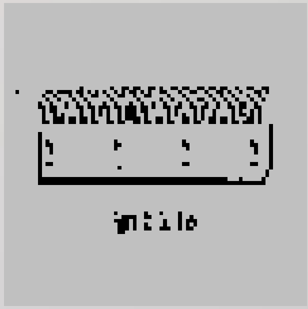
$$T_2 = 6 \cdot T_0$$

Increase torque

$$V_2 = \frac{1}{6} \cdot V_0$$

Decrease speed

<u>Gears: Types and Descriptions</u>

Spur Gears	Helical Gears	Bevel Gears	Worm Gears	Straight Gears
				

Motors Interfacing and PID controllers

Servo Motor

A servo motor is provided with a controller which continuously adjusts the electrical current to the motor in order to reach a set-point position.

It is provided with 3-wires:

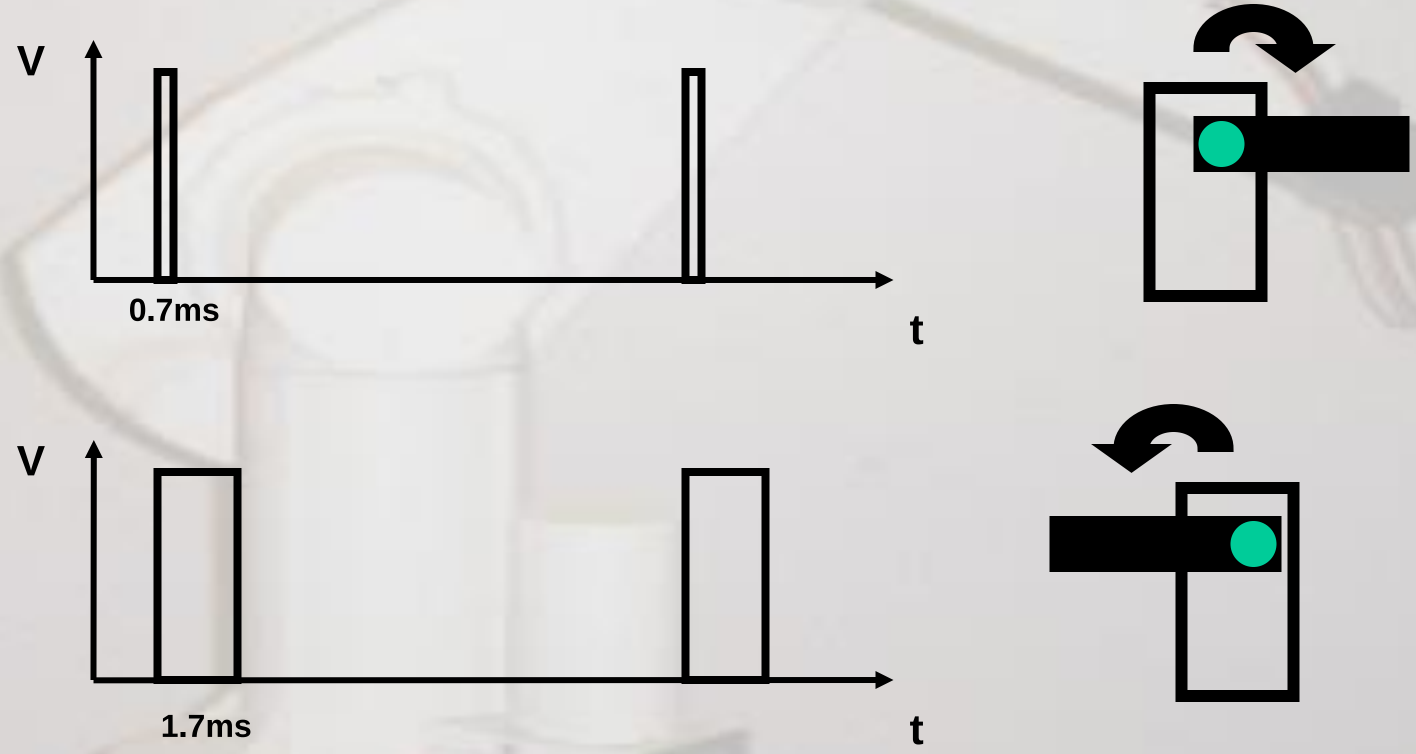
1. power,
2. ground,
3. control input with pulse-width signal to determine the position the motor should servo.

The motor elements consist of a:

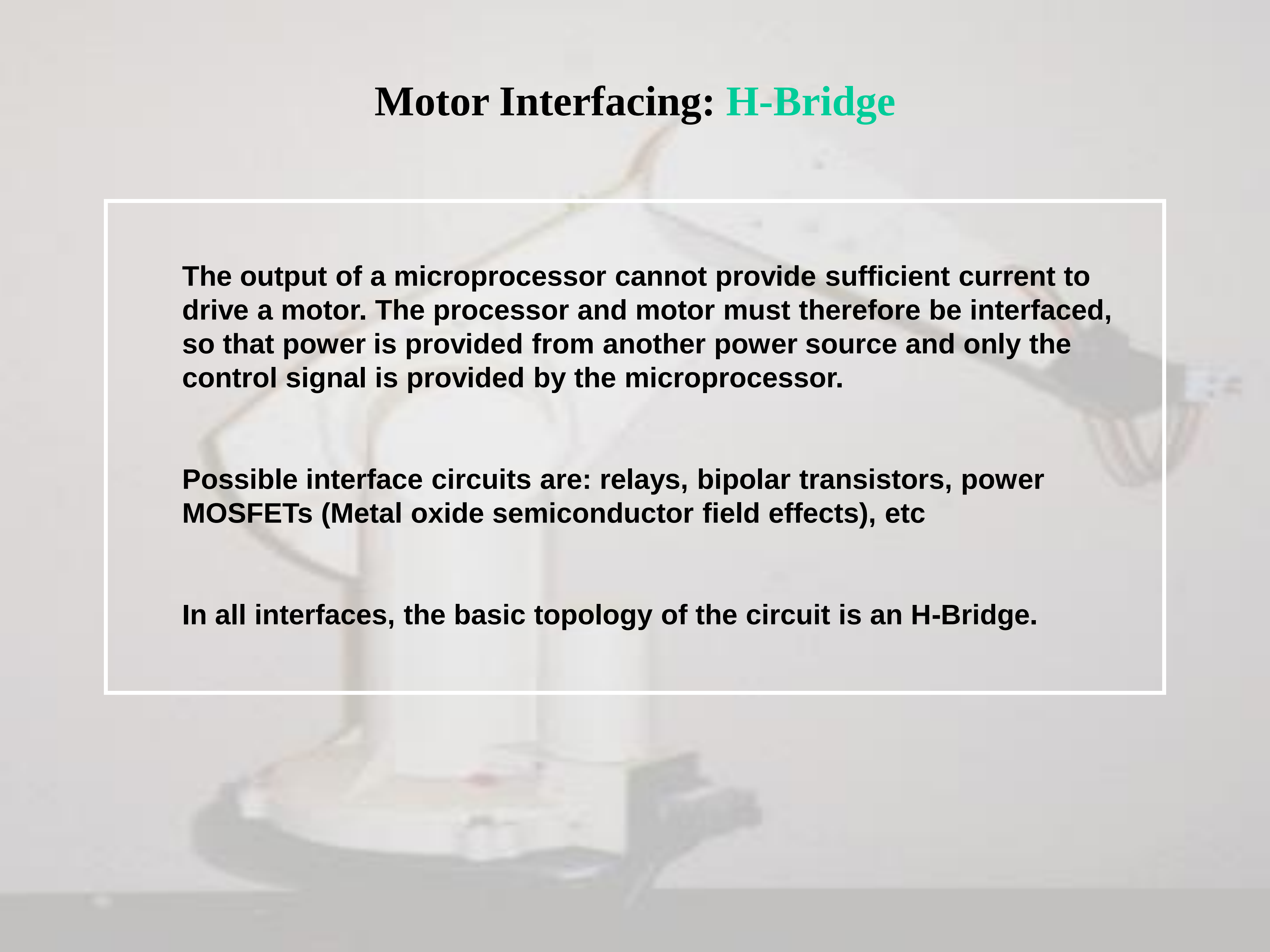
- DC motor
- gear train
- limit stops beyond which the shaft cannot turn
- a potentiometer for position feedback
- an integrated circuit for position control

Servo Motor

A motor servo expects a pulse-code modulated signal, which the servo interprets as defining a desired position on the potentiometer.



Motor Interfacing: H-Bridge



The output of a microprocessor cannot provide sufficient current to drive a motor. The processor and motor must therefore be interfaced, so that power is provided from another power source and only the control signal is provided by the microprocessor.

Possible interface circuits are: relays, bipolar transistors, power MOSFETs (Metal oxide semiconductor field effects), etc

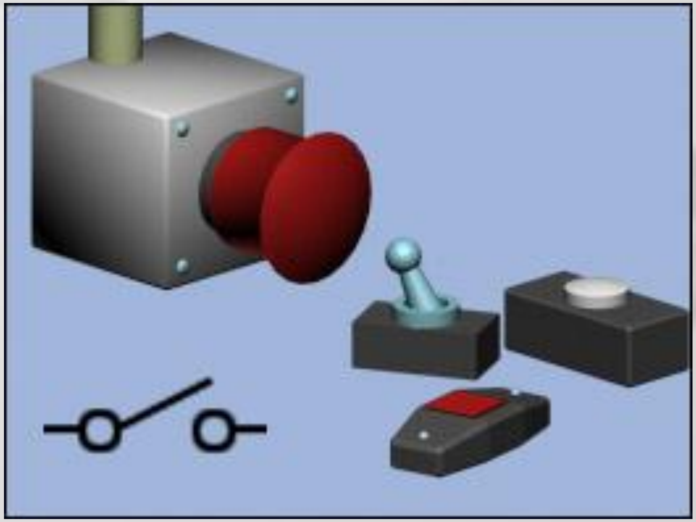
In all interfaces, the basic topology of the circuit is an H-Bridge.

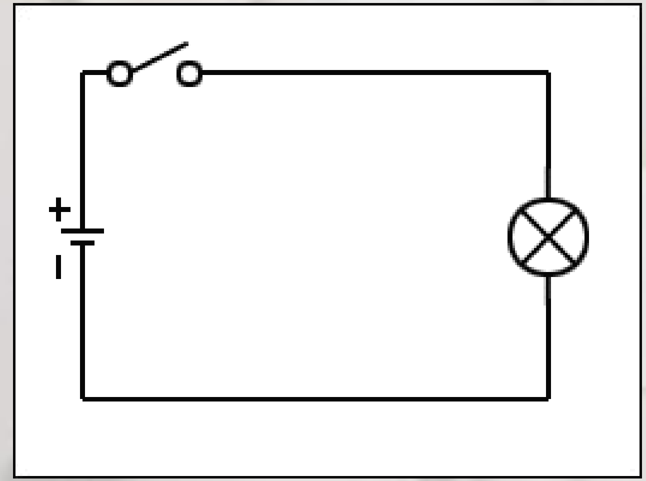
BASIC ELECTRONIC COMPONENTS

SWITCHES

A switch opens and closes a circuit.

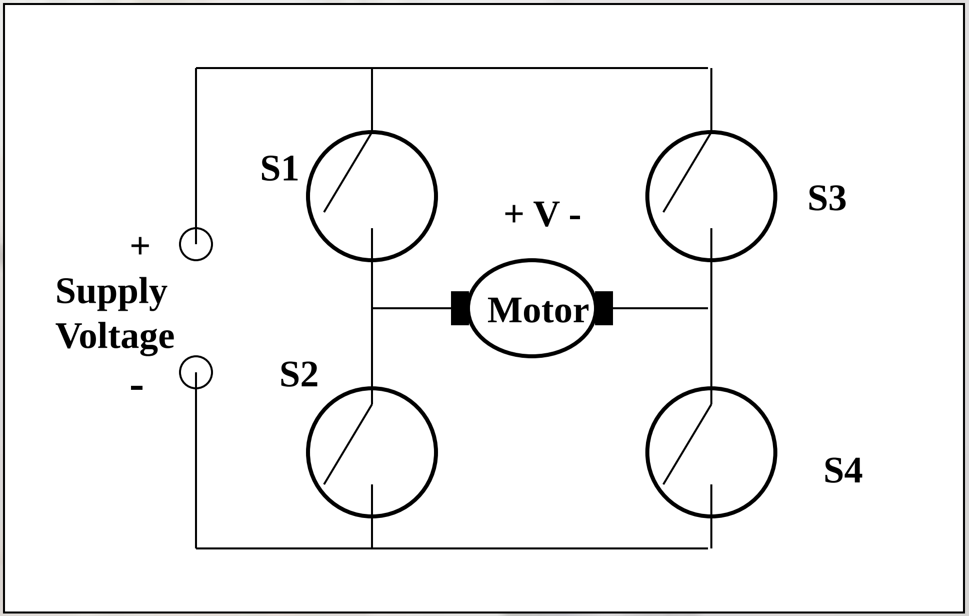
The current flows in when the circuit is closed.





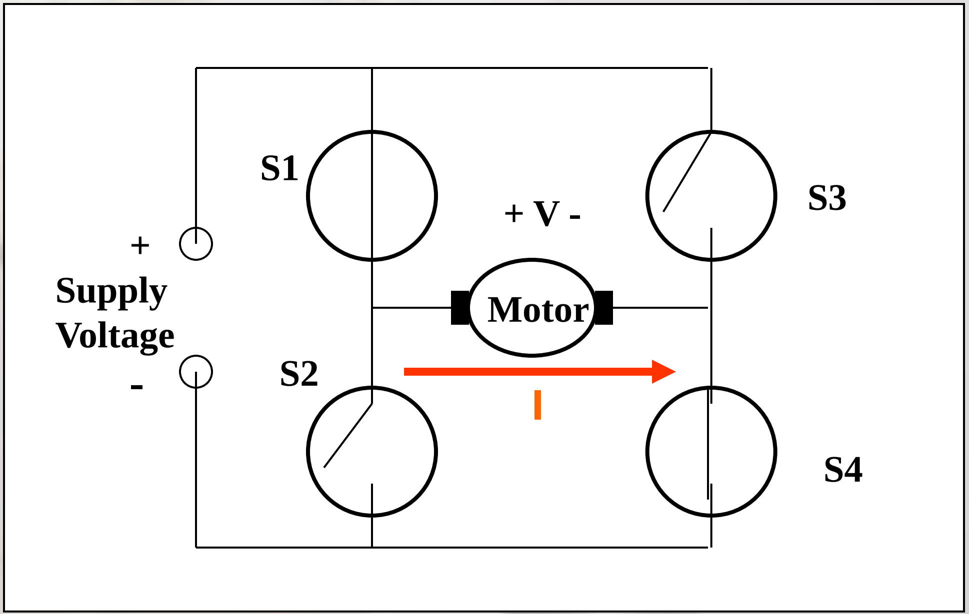
Motor Interfacing: H-Bridge

Switches are open or closed to put a voltage of one polarity, causing current to flow through the motor in one direction.



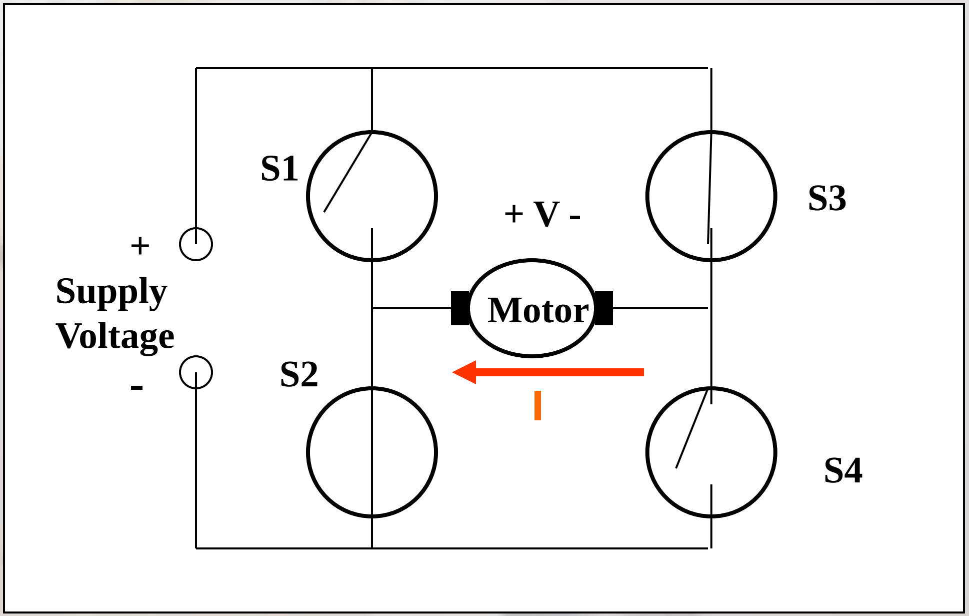
Motor Interfacing: H-Bridge

S1, S4 Closed and S2, S3 Open: current flows from left to right

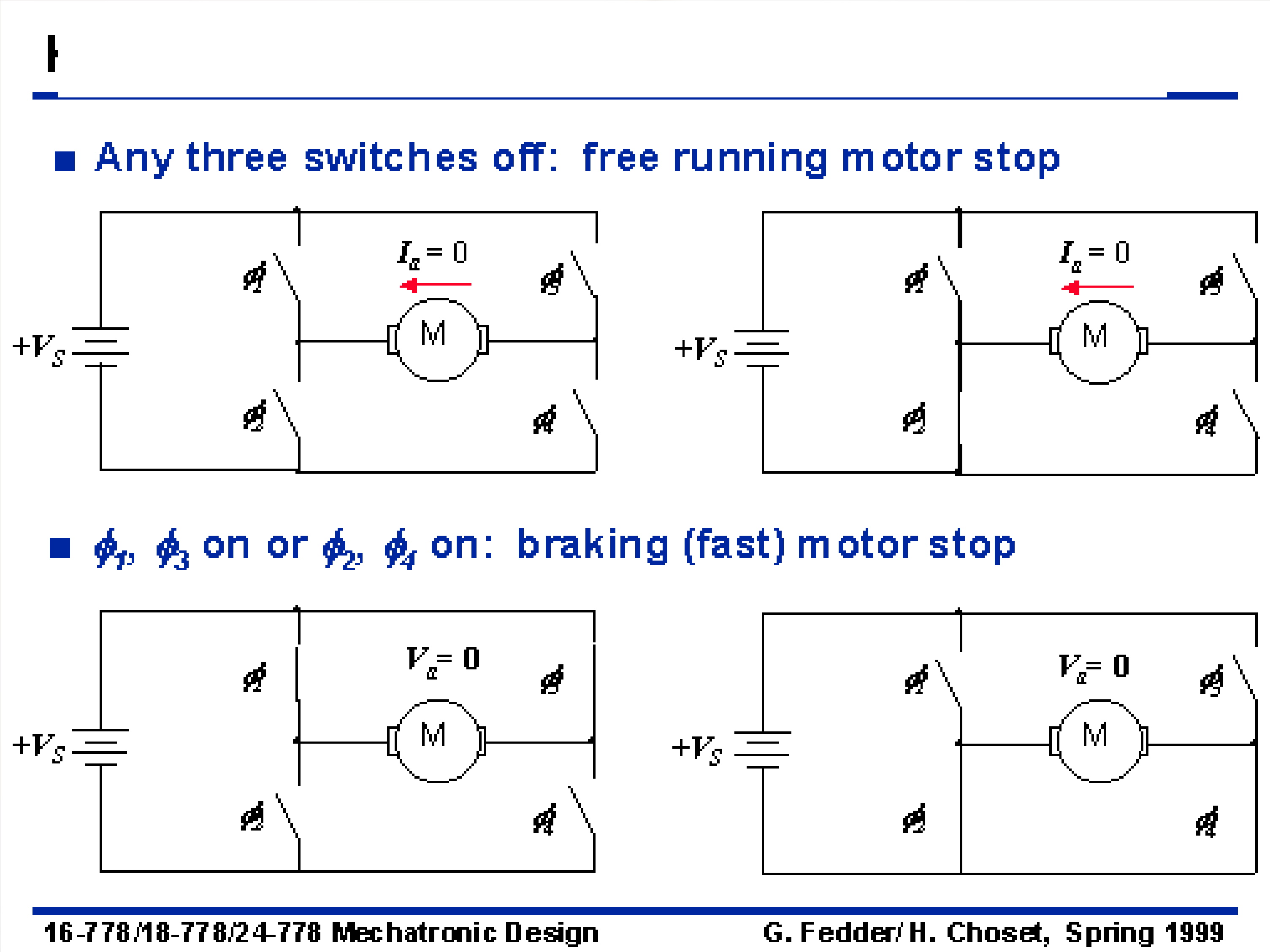


Motor Interfacing: H-Bridge

S1, S4 Open and S2, S3 Closed: current flows from right to left



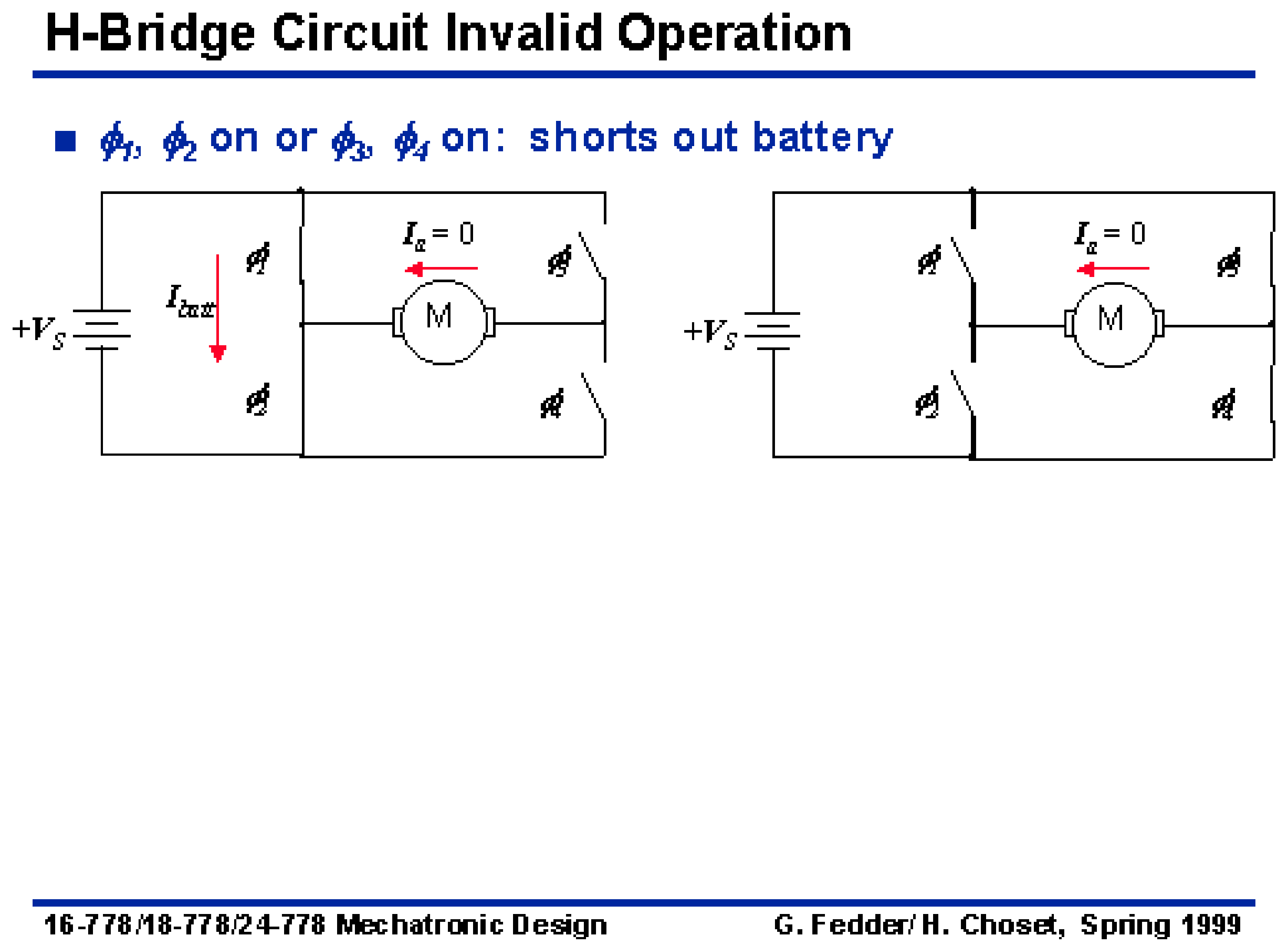
Motor Interfacing: H-Bridge



- Any three switches off: free running motor stop

- ϕ_1, ϕ_3 on or ϕ_2, ϕ_4 on: braking (fast) motor stop

Motor Interfacing: H-Bridge



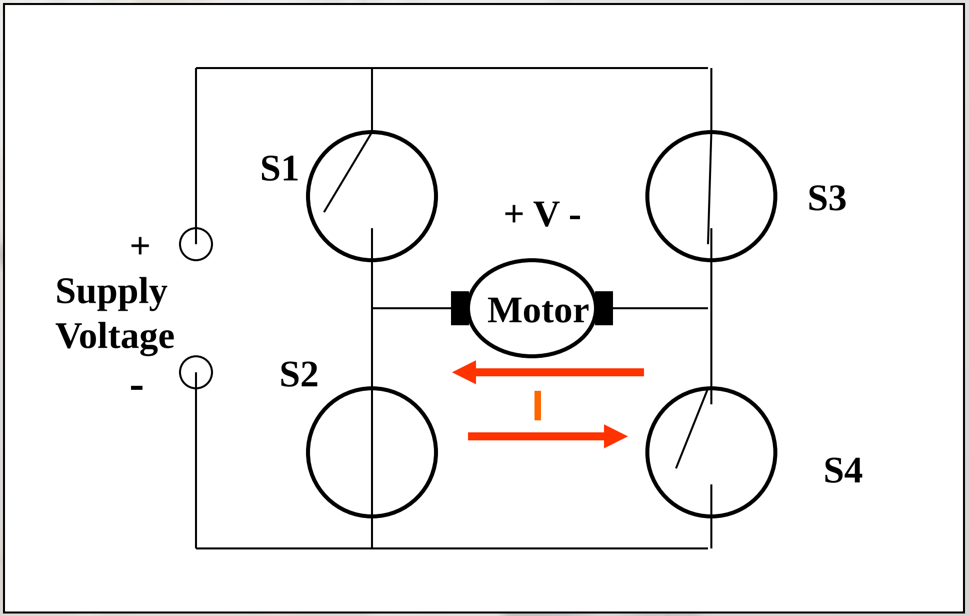
H-Bridge Circuit Invalid Operation

- ϕ_1, ϕ_2 on or ϕ_3, ϕ_4 on: shorts out battery

Motor Interfacing: H-Bridge

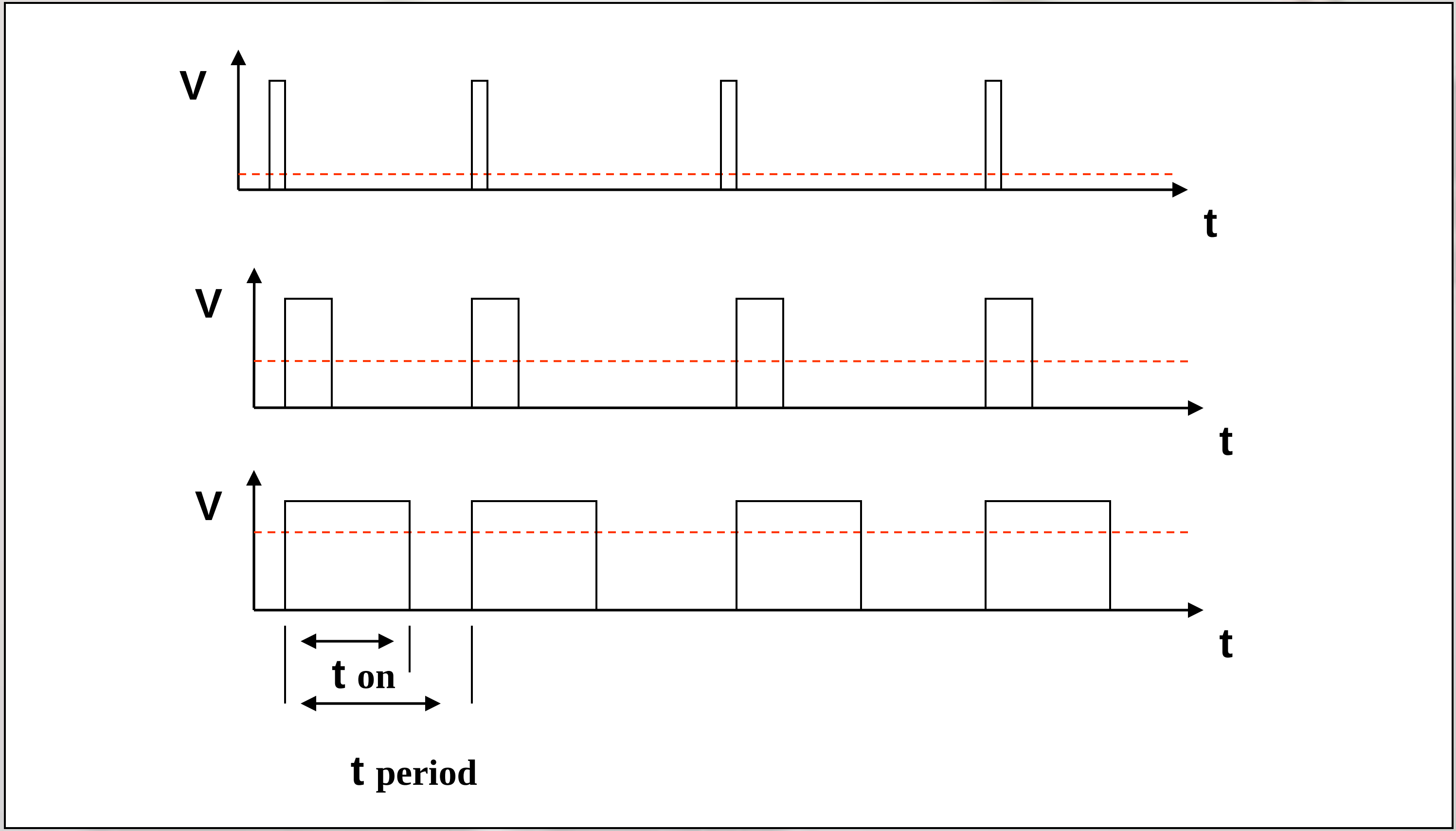
The speed of a DC motor is controlled by *pulse-width modulation,* by opening and closing the switches at different rates to vary the average voltage across the motor.

Pulse-width modulation is different from pulse-code for servo motors.



Motor Interfacing: H-Bridge

$$Pulse - Width - Ratio = \frac{t_{on}}{t_{period}}$$



Motor Interfacing: H-Bridge

There are a number of single-chip H-bridge controller.

The five motors of ROBOTA 5 are interfaced using a Texas Instrument chip: TPIC0107B, PWM Control Intelligent H-Bridge.