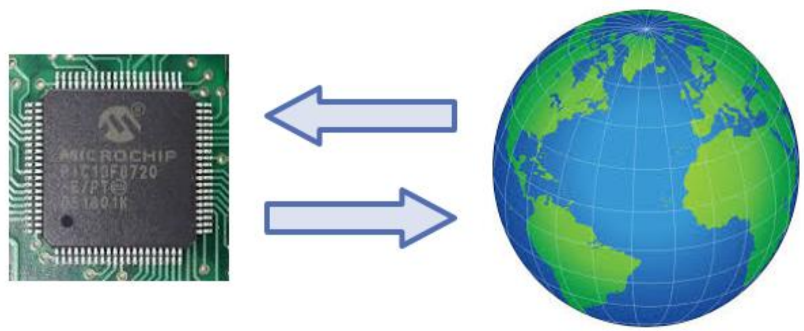
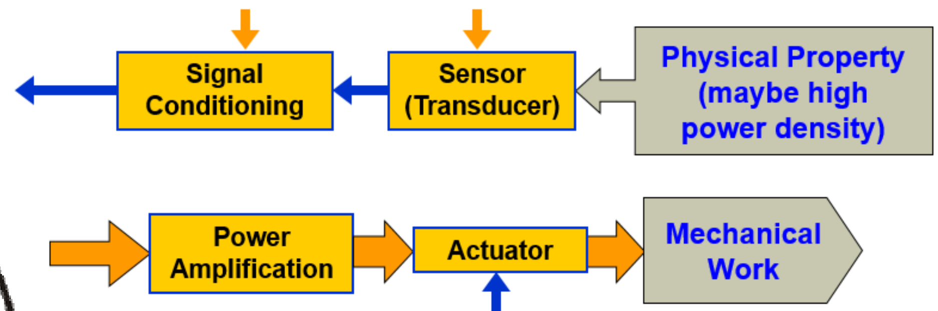
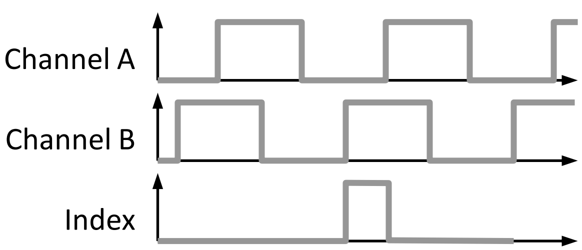
FROM LAST TIME…

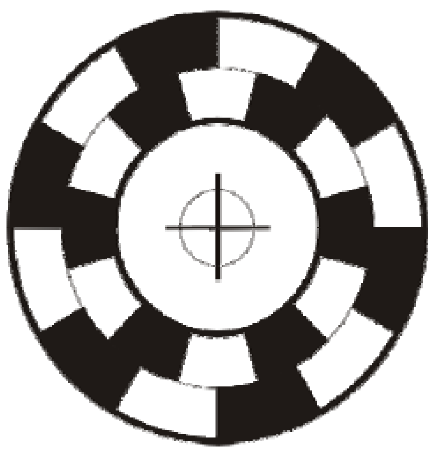
System Interfacing (Position and Velocity sensors)

- Analog vs. Digital sensors
- Analog and Digital Position sensors
- Analog and Digital Velocity sensors



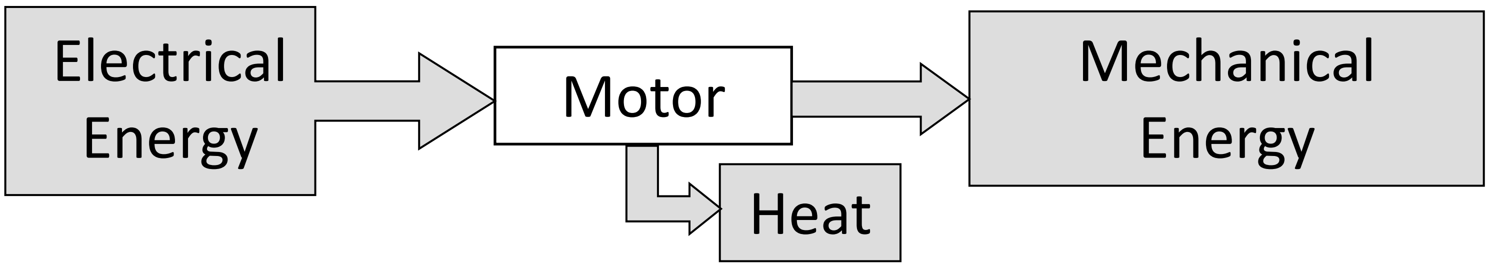






UNIT 8:
DC MOTORS

AN ELECTRIC MOTOR CONVERTS ELEC. ENERGY INTO MECH. ENERGY



Energy conversion in electric motors is most commonly based on ***electromagnetism***. AC motors rely on *alternating current* to establish the desired magnetic fields, while DC motors use *direct current*.

Electrical Energy In > Mechanical Energy Out

ELECTRIC MOTORS

- Electric Motors
  - DC Motors
    - Brushed
      - Permanent Magnet
      - Series Wound
      - Shunt Wound
      - Compounded
      - Separately Excited
    - Brushless
      - Stepper
  - AC Motors
    - Synchronous
      - Reluctance
      - Hysteresis
      - Permanent Magnet
    - Induction
      - Wound Rotor
      - Squirrel Cage

AC AND DC MOTORS USUALLY EXHIBIT CERTAIN CHARACTERISTICS

DC Motors:

- Pros: Simple control, inexpensive, good for ***variable speed*** applications
- Cons: Shorter life-span, higher maintenance costs, limited to ***low power*** applications

AC Motors:

- Pros: Simple design, ***high power*** factor, long life, good for ***fixed speed*** applications
- Cons: More complex control, poor low speed performance, poor position control

AC AND DC MOTORS USUALLY EXHIBIT CERTAIN CHARACTERISTICS

DC Motors:

- Pros: Simple control, inexpensive, good for variable speed applications
- Cons: ... e costs,

AC Motors:

- Pros: Simple design, high power factor, long life, good for fixed speed applications
- Cons: More complex control, poor low speed performance, poor position control

AC motors becoming more prevalent with advancing control technology…

AC AND DC MOTORS USUALLY EXHIBIT CERTAIN CHARACTERISTICS

DC Motors:

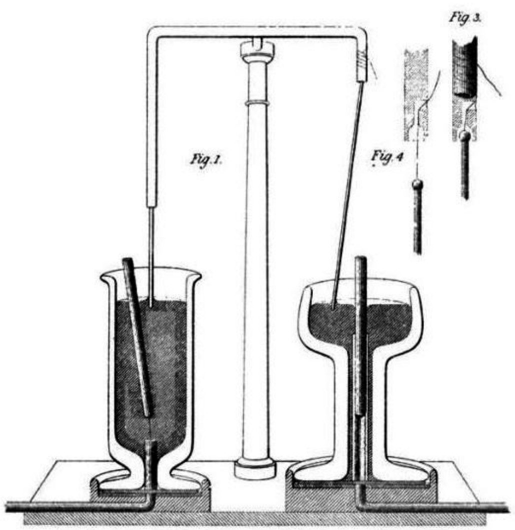
- Pros: Simple control, inexpensive, good for variable speed applications
- Cons: … e costs,

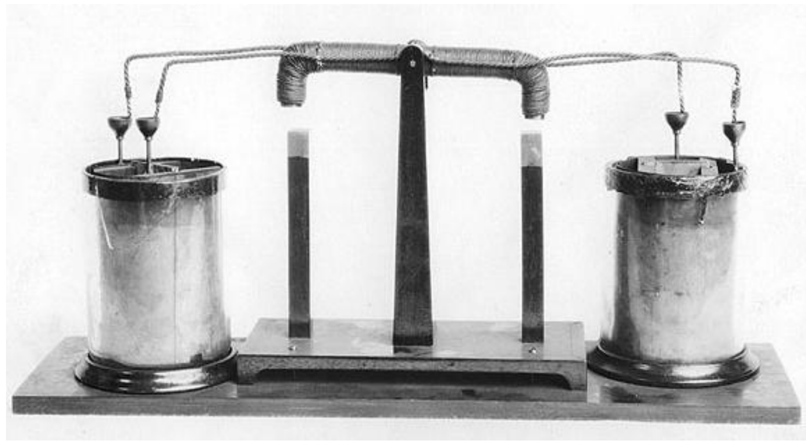
AC Motors:

- Pros: Simple design, high power factor, long life, good for fixed speed applications
- Cons: More complex control, poor low speed performance, poor position control

… but DC motors are still widely used in low-power applications

THE DC MOTOR WAS DEVELOPED IN THE 19TH CENTURY

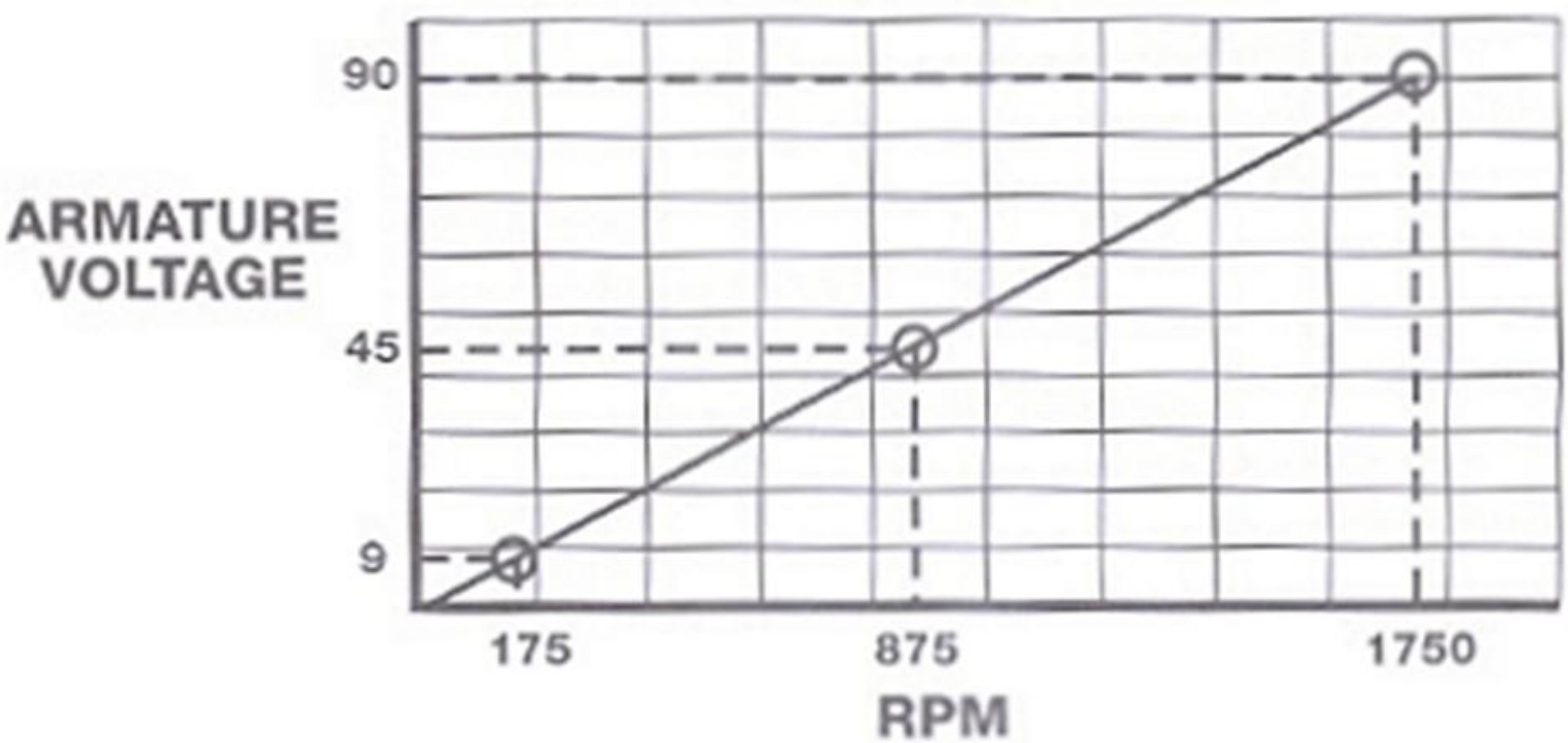




- Faraday (1821) demonstrated a magnetic field around a current-carrying wire
- Henry (1831) built a rocking electromagnet at 75 Hz
- Sturgeon (1832) invented the commutator and rotary electric motor

DC MOTORS ARE VERY EASY TO CONTROL

- Increase voltage to increase speed
- Reverse voltage to reverse direction



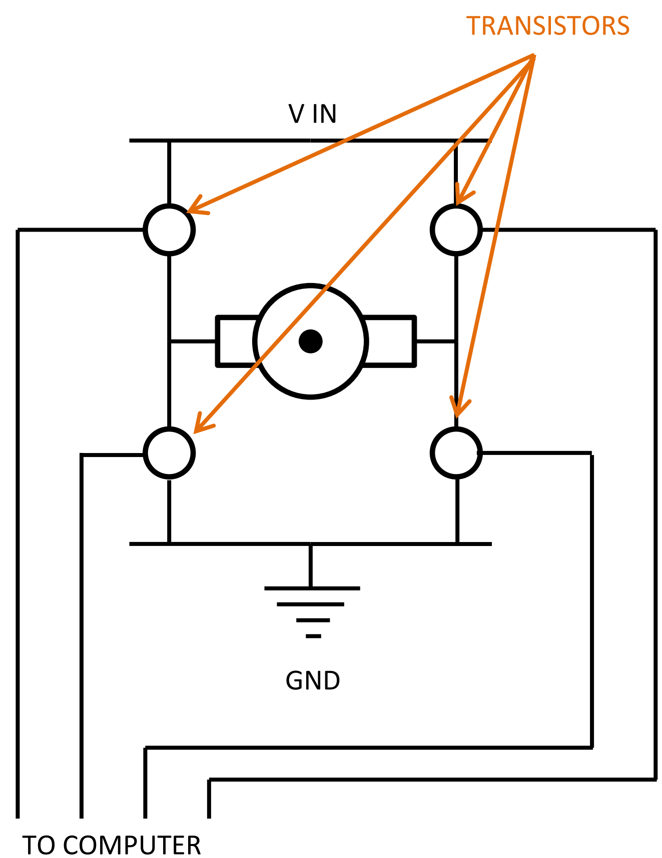
DC MOTOR SPEED IS CONTROLLED WITH AN INPUT VOLTAGE

$2.95 each

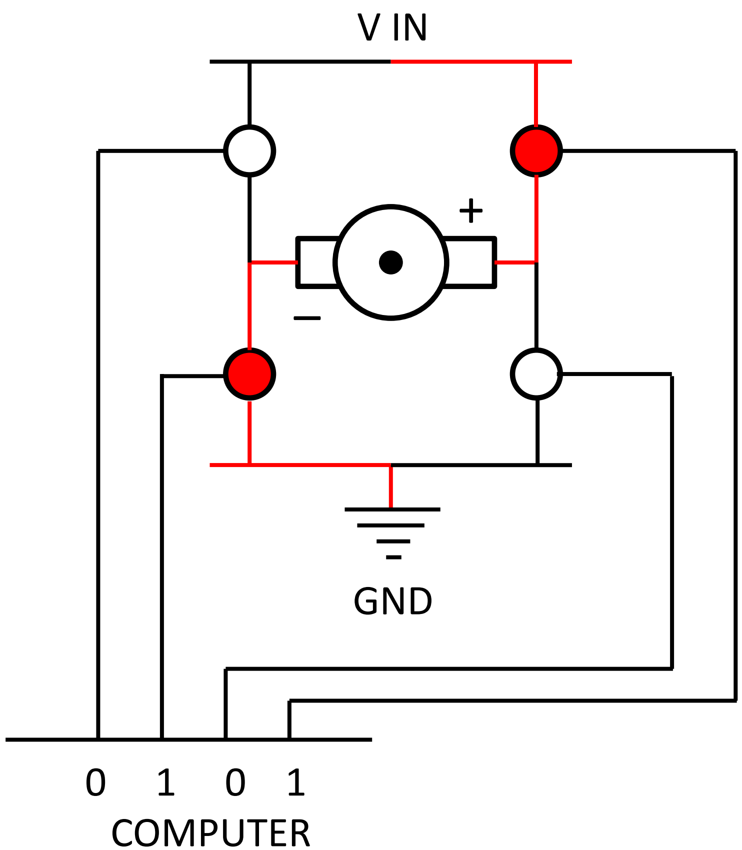
Image: http://www.surplustraders.net/specialist/24VDC%20MOTOR-MF858

AN H-BRIDGE IS USED TO CONTROL SPEED AND DIRECTION

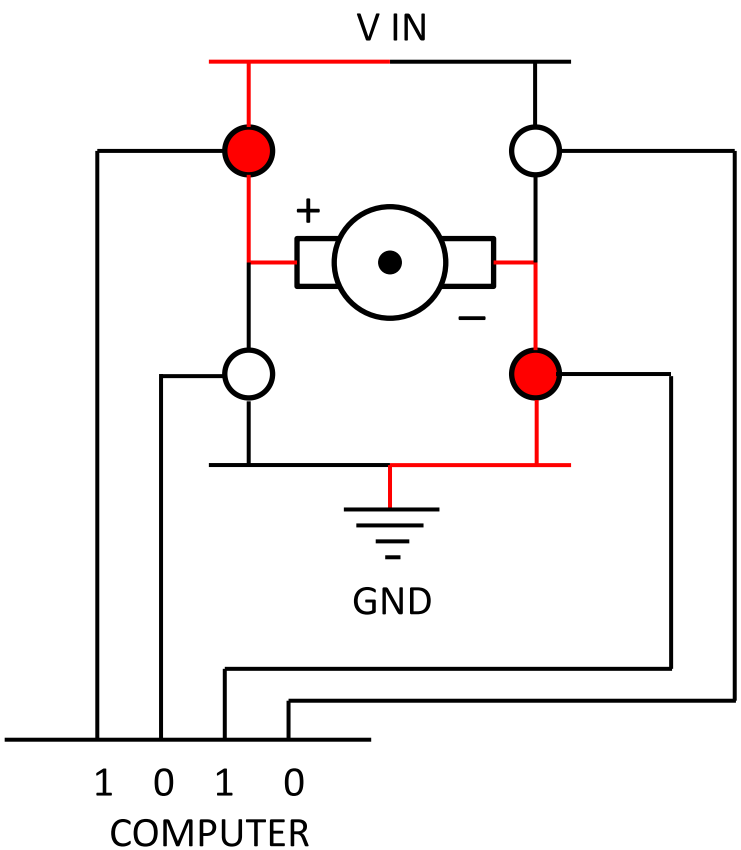
- Name derived from shape of circuit
- Four switches (usually transistors) control circuit behavior
- Two switches turned on at a time
- Bipolar operation with unipolar supply voltage
- Speed is set by input voltage



AN H-BRIDGE IS USED TO CONTROL SPEED AND DIRECTION



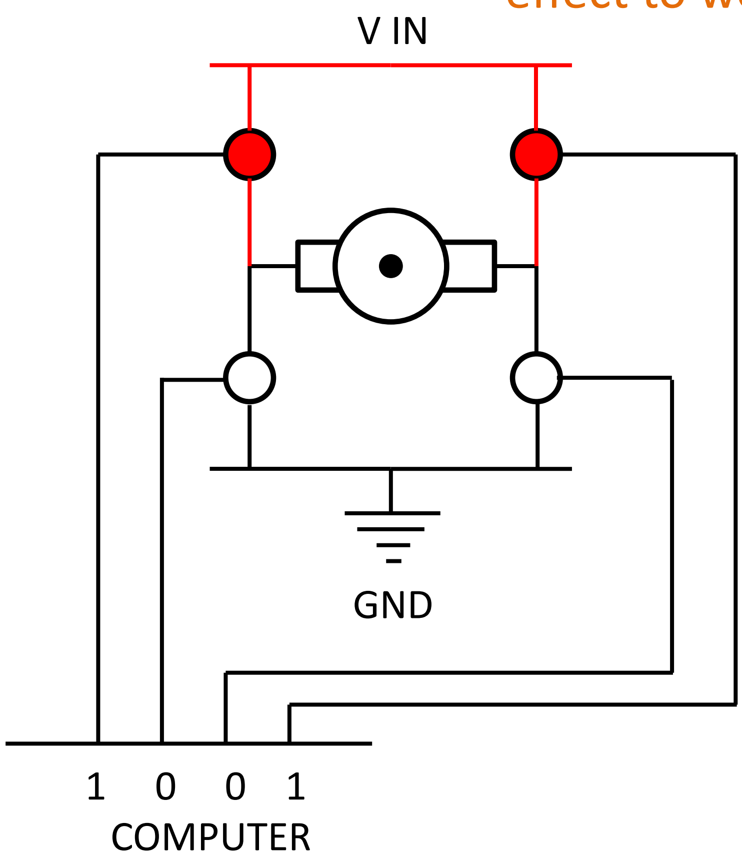
Forward Operation



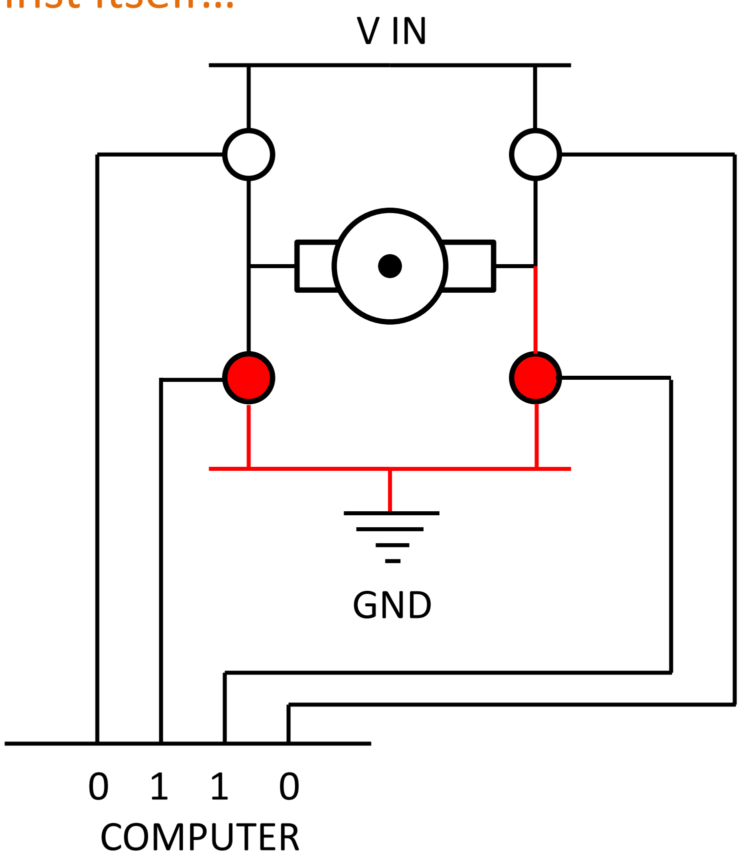
Reverse Operation

AN H-BRIDGE IS USED TO CONTROL SPEED AND DIRECTION

Connecting motor leads causes the motor's generator effect to work against itself…

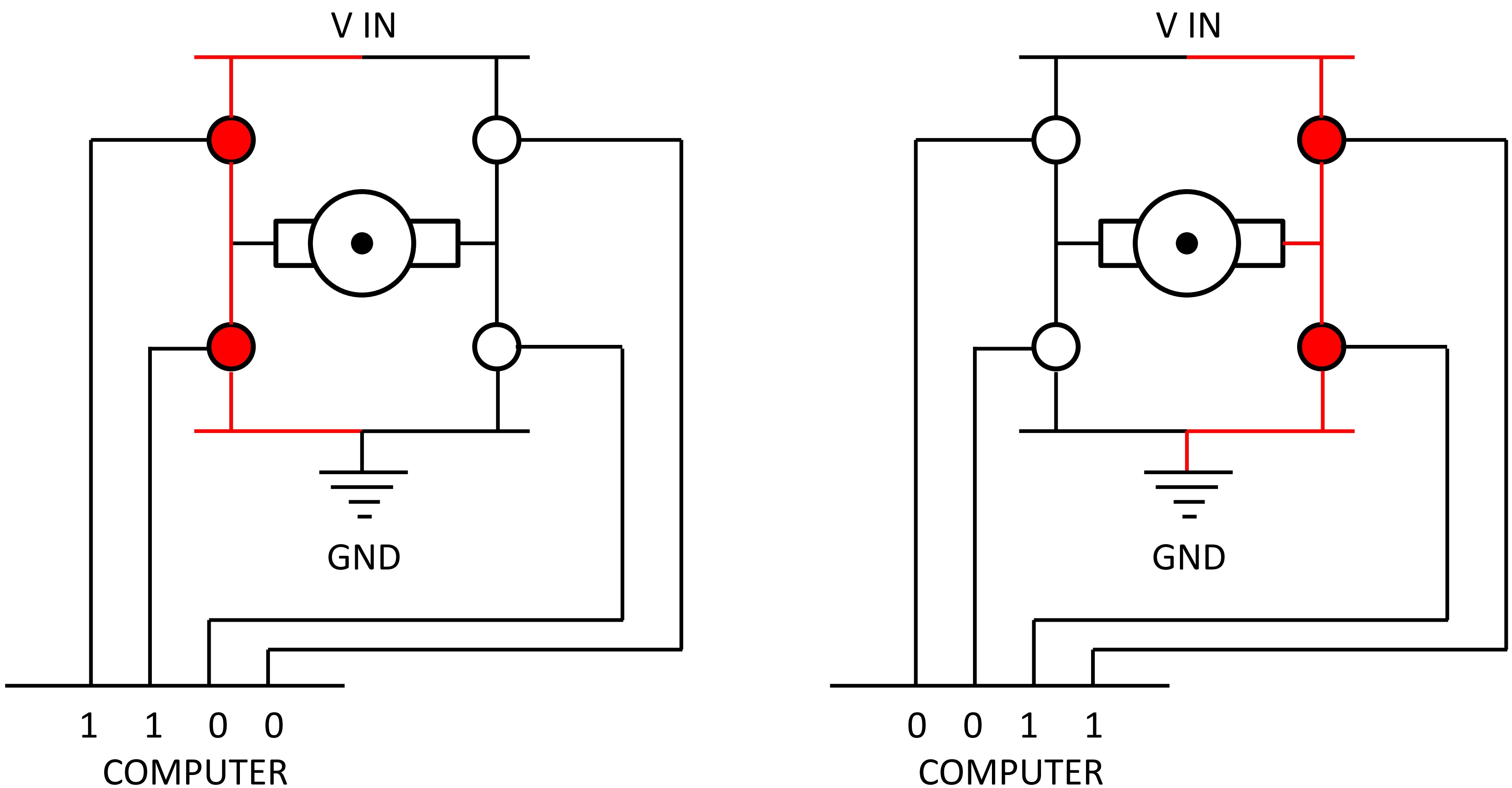


Braking Operation



Braking Operation

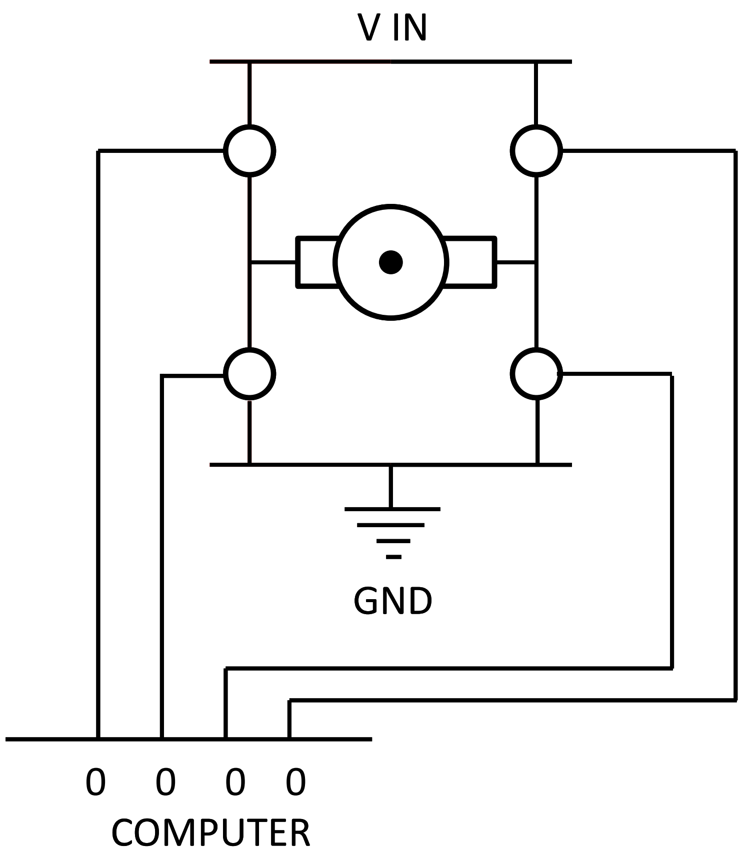
AN H-BRIDGE IS USED TO CONTROL SPEED AND DIRECTION



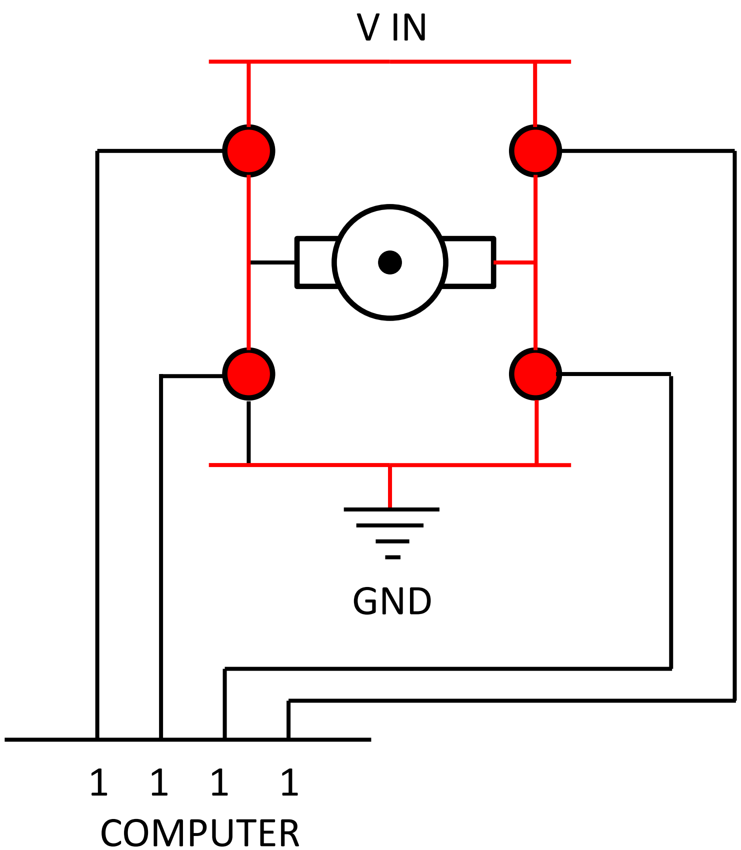
"Shoot thru" (not desirable)

"Shoot thru" (not desirable)

AN H-BRIDGE IS USED TO CONTROL SPEED AND DIRECTION



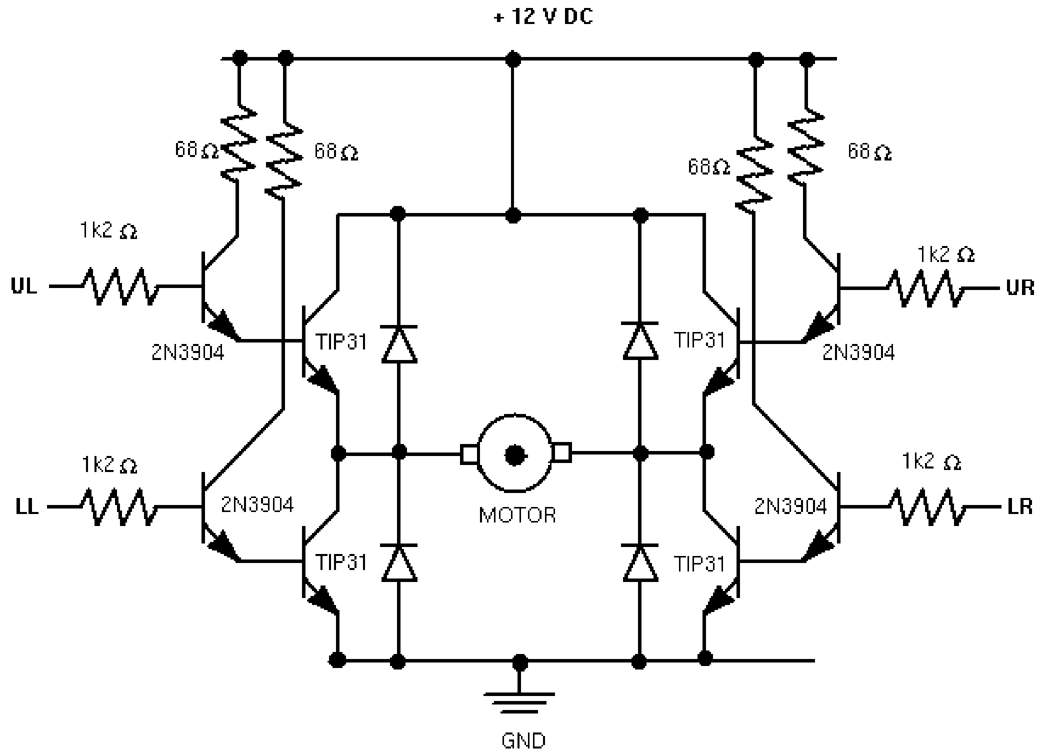
Motor "free run"



"Shoot thru" (not desirable)

AN H-BRIDGE IS USED TO CONTROL SPEED AND DIRECTION

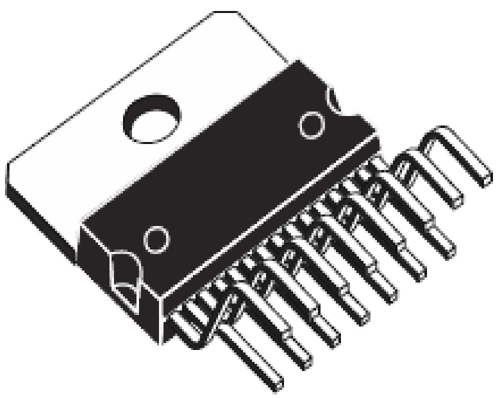
- Circuit Example



Upper Left	Upper Right	Lower Left	Lower Right	Description
On	Off	Off	On	Forward Running
Off	On	On	Off	Backward Running
On	On	Off	Off	Braking
Off	Off	On	On	Braking

H-BRIDGE DRIVERS ARE COMMERCIALLY AVAILABLE

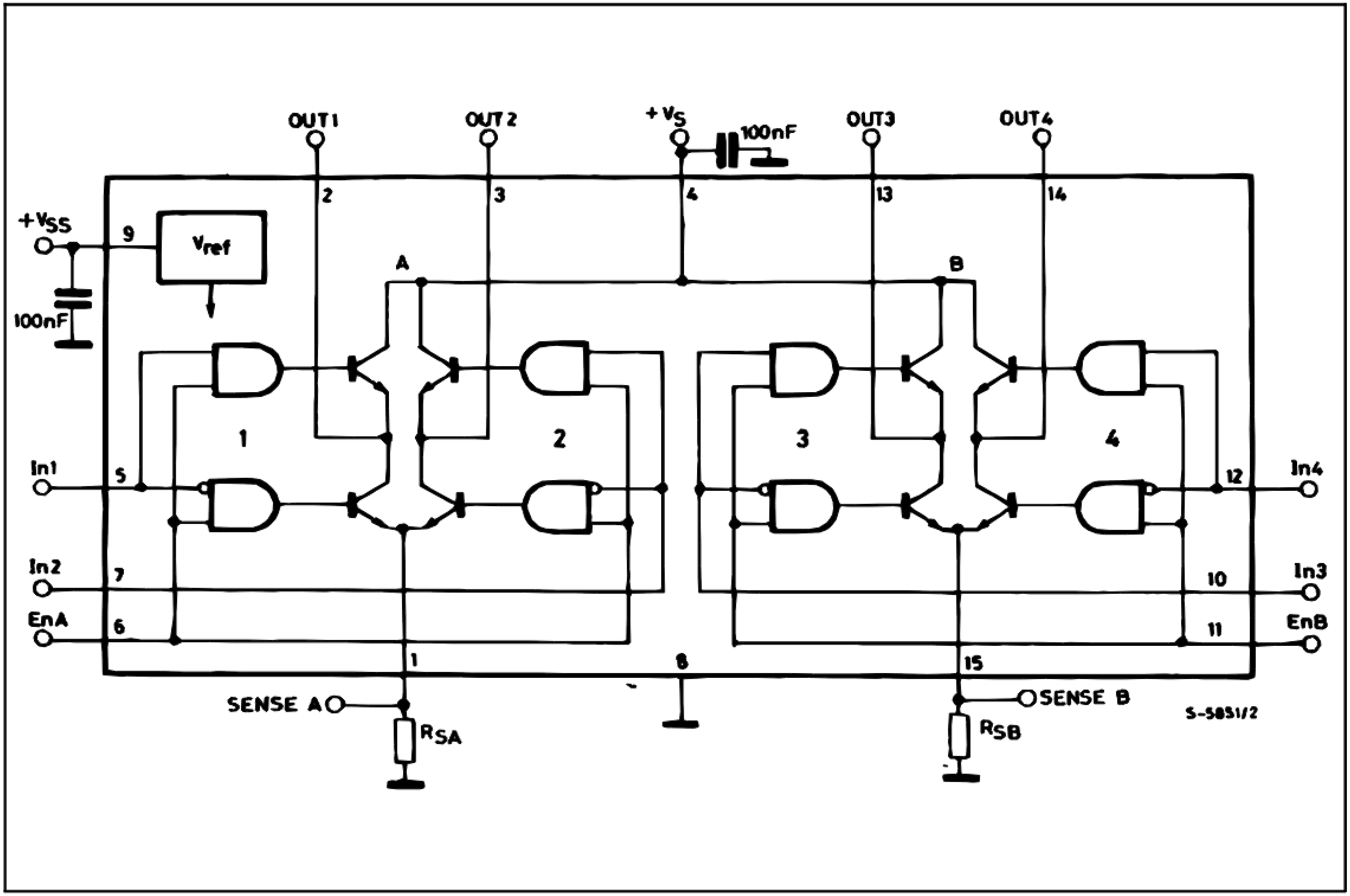
- A popular motor driver is the L298
- Flyback diodes not always incorporated into commercial ICs!
- In addition to 4 switch inputs, L298 incorporates "enable" pins



L298 Multiwatt15 package

L298 MOTOR DRIVER

BLOCK DIAGRAM



A DC MOTOR CAN BE DRIVEN USING A PWM SIGNAL

- Can run PWM signal through an H-bridge to drive the DC motor
- PWM behaves most linearly near 50% duty cycle; linearity drops off at the extremes.
- Arduino Uno supplies 6 PWM output pins

DC MOTOR SPECIFICATIONS

Nominal voltage is the input voltage used to establish published specifications. You can apply higher and lower voltages, but watch out not to exceed max. current ratings!

			118749	118750	118751	118752	118753	118754	118755	118756	118757
Motor Data											
1	Assigned power rating	W				20					
2	Nominal voltage	Volt				24.0					
3	No load speed	rpm				9660					
4	Stall torque	mNm				240					
5	Speed / torque gradient	rpm / mNm				41.2					
6	No load current	mA				37					
7	Starting current	mA				10300					
8	Terminal resistance	Ohm				2.32					
9	Max. permissible speed	rpm				11000					
10	Max. continuous current	mA				1230					
11	Max. continuous torque	mNm				28.4					
12	Max. power output at nominal voltage	mW				58400					
13	Max. efficiency	%				85					
14	Torque constant	mNm / A				23.2					
15	Speed constant	rpm / V				412					
16	Mechanical time constant	ms				5					
17	Rotor inertia	gcm^2				10.3					
18	Terminal inductance	mH				0.24					
19	Thermal resistance housing-ambient	K / W				14					
20	Thermal resistance rotor-housing	K / W				3.1					
21	Thermal time constant winding	s				12					

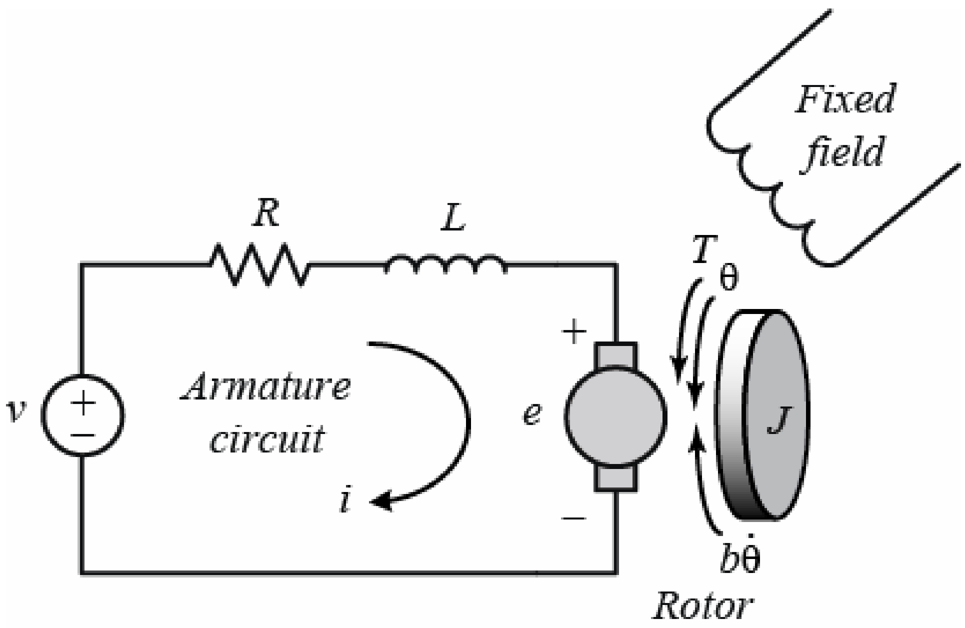
FACTORS TO CONSIDER WHEN SELECTING A MOTOR

While the nominal voltage is not an absolute definition of the operating voltage, it's a pretty good guideline:

- If you apply a voltage far above the nominal voltage, you risk overheating the motor (due to too much current).

- If you apply a voltage far below the nominal voltage, you may not overcome the motor's internal friction (too little current and, hence, too little torque).

DC MOTORS FUNCTION USING TWO FUNDAMENTAL PRINCIPLES

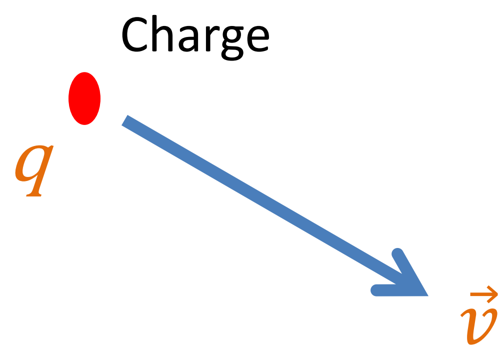


- **Torque Production:** current-carrying conductor in magnetic field will induce electro-magnetic force acting on the conductor
- **Back EMF:** electric potential will be generated across moving conductor in magnetic field

ELEC. CURRENT AND MAGNETIC FIELD INTERACT TO PRODUCE FORCE

- Lorentz Force

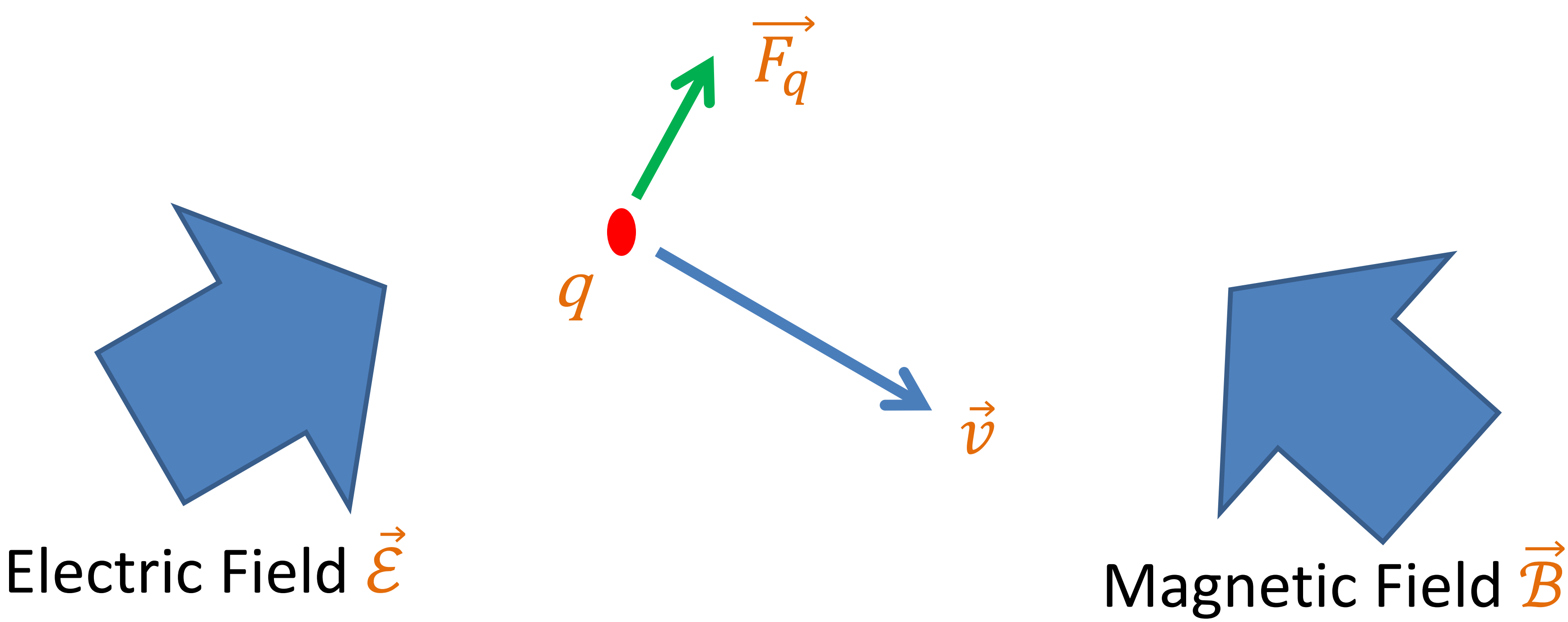
  Consider a charge q passing through space with velocity v…



ELEC. CURRENT AND MAGNETIC FIELD INTERACT TO PRODUCE FORCE

- Lorentz Force

  A force is generated on the charge if it passes through an electric ***or*** magnetic field.



ELEC. CURRENT AND MAGNETIC FIELD INTERACT TO PRODUCE FORCE

- Lorentz Force

  Specifically, the force $\overrightarrow{F_q}$ acting on electrical charge q, when the charge is moving with instantaneous velocity $\vec{v}$, through external electric field $\vec{\mathcal{E}}$ and magnetic field $\vec{\mathcal{B}}$, is given by:

$$\overrightarrow{F_q} = \underbrace{q\vec{\mathcal{E}}}_{\text{Electric Force}} + \underbrace{q(\vec{v} \times \vec{\mathcal{B}})}_{\text{Magnetic Force}}$$

ELEC. CURRENT AND MAGNETIC FIELD INTERACT TO PRODUCE FORCE

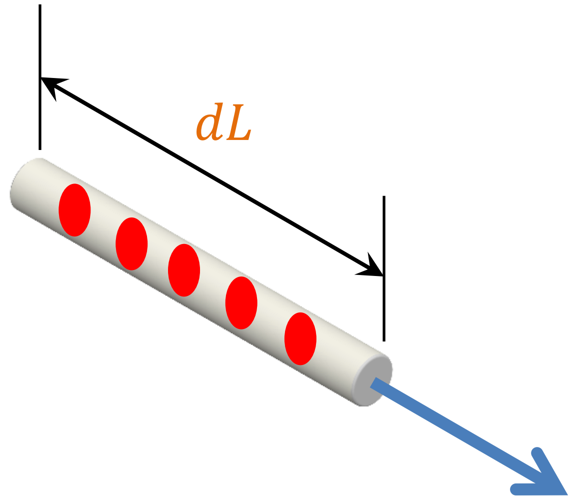
- Lorentz Force

  In a region with no external electric field $\vec{\mathcal{E}}$:

$$\overrightarrow{F_q} = q(\vec{v} \times \vec{\mathcal{B}})$$

ELEC. CURRENT AND MAGNETIC FIELD INTERACT TO PRODUCE FORCE

- Lorentz Force

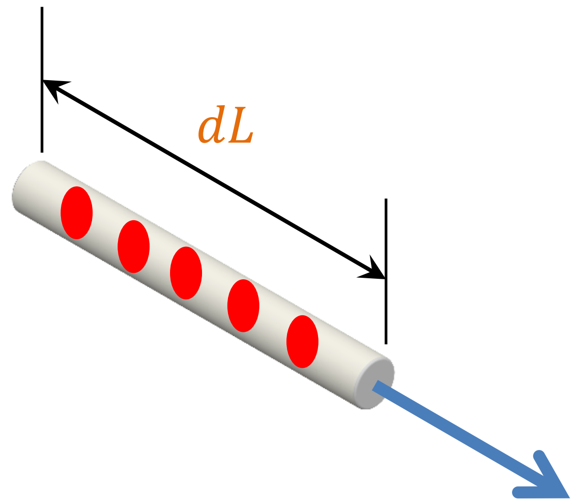


Let charges of linear density λ pass through an infinitesimally short length of wire dL within magnetic field $\overrightarrow{\mathcal{B}}$. Then the infinitesimal force acting on ***all charges*** in that differential length of wire is:

$$\overrightarrow{dF} = \lambda \cdot dL \cdot \vec{v} \times \overrightarrow{\mathcal{B}}$$

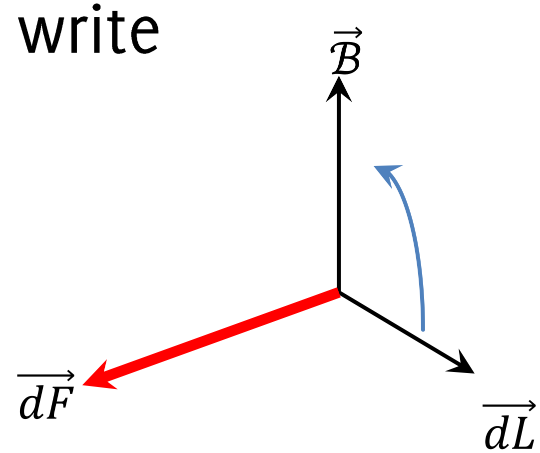
ELEC. CURRENT AND MAGNETIC FIELD INTERACT TO PRODUCE FORCE

- Lorentz Force



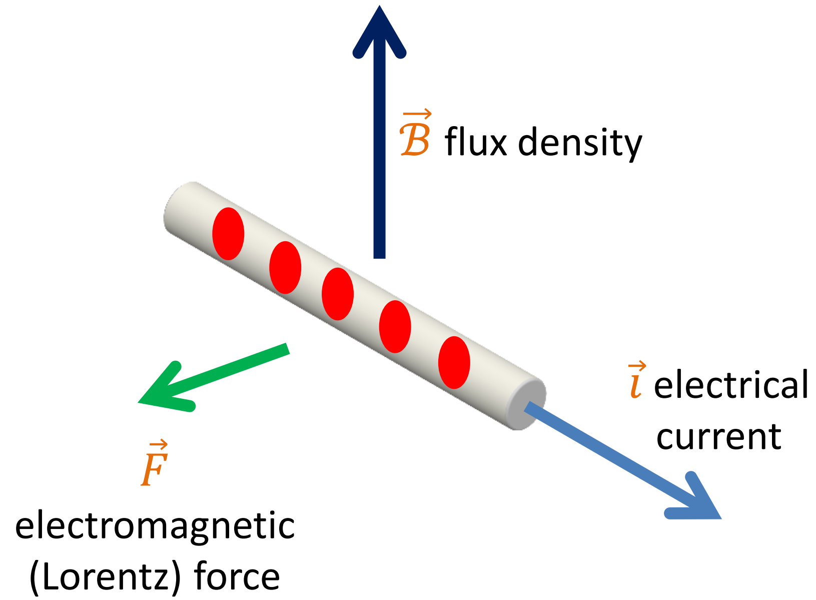
Since current $\vec{I} = \lambda \cdot \vec{v}$, and wire length $\overrightarrow{dL}$ points in the same direction as the current flow, we can treat current as a scalar value, and write

$$\overrightarrow{dF} = I \cdot \overrightarrow{dL} \times \overrightarrow{\mathcal{B}}$$



ELEC. CURRENT AND MAGNETIC FIELD INTERACT TO PRODUCE FORCE

- Lorentz Force



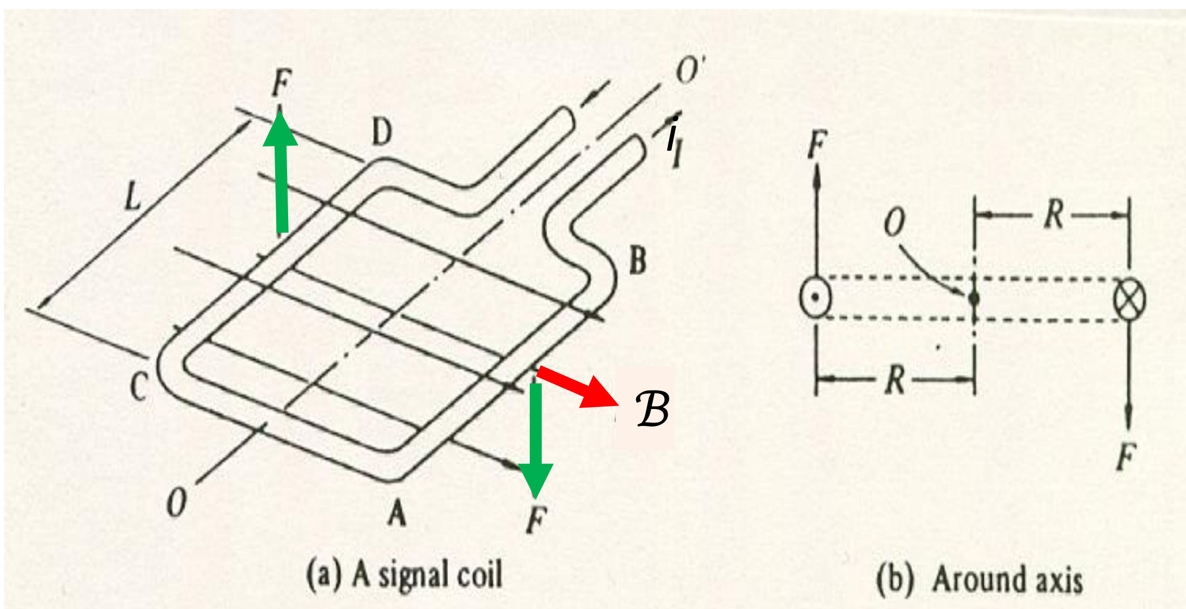
So we can generate (and eventually control) the force acting on a conductor if we are able to provide (and regulate) two elements:

- **Magnetic field**
- **Electric current**

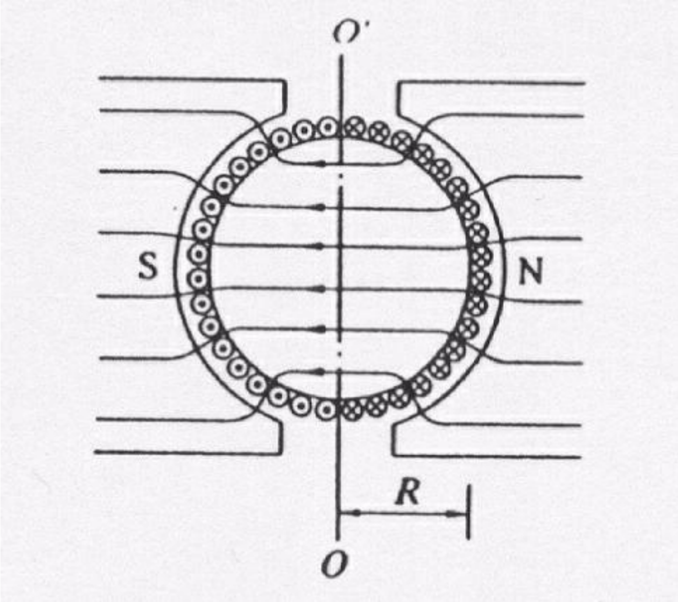
TORQUE RESULTS FROM FORCE APPLIED ABOUT A CENTER AXIS

- Integrate over the entire length: $F = i \cdot L \cdot \mathcal{B}$

- Total torque generated: $\tau_{coil} = 2 \cdot F \cdot R$
  $= 2 \cdot (i \cdot L \cdot \mathcal{B}) \cdot R$



TORQUE RESULTS FROM FORCE APPLIED ABOUT A CENTER AXIS



Let N be the number of coils in the motor. The total torque generated from the N coils is:

$$T_M = N \cdot (2 \cdot i \cdot \mathcal{B} \cdot L \cdot R)$$
$$= 2 \cdot (N \cdot \mathcal{B} \cdot L \cdot R) \cdot i$$

For a given motor, (N, $\mathcal{B}$, L, R) are fixed. We can therefore define the motor's ***torque constant*** as:

$$K_T = 2 \cdot N \cdot \mathcal{B} \cdot L \cdot R \qquad [\mathrm{Nm/A}]$$

The torque generated by a DC motor is proportional to the armature current, i_a:

$$T_M = K_T \cdot i_a$$

DC MOTOR SPECIFICATIONS

$$T_M = K_T \cdot i_a$$

			118749	118750	118751	118752	118753	118754	118755	118756	118757
Motor Data											
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2	Nominal voltage	Volt				24.0					
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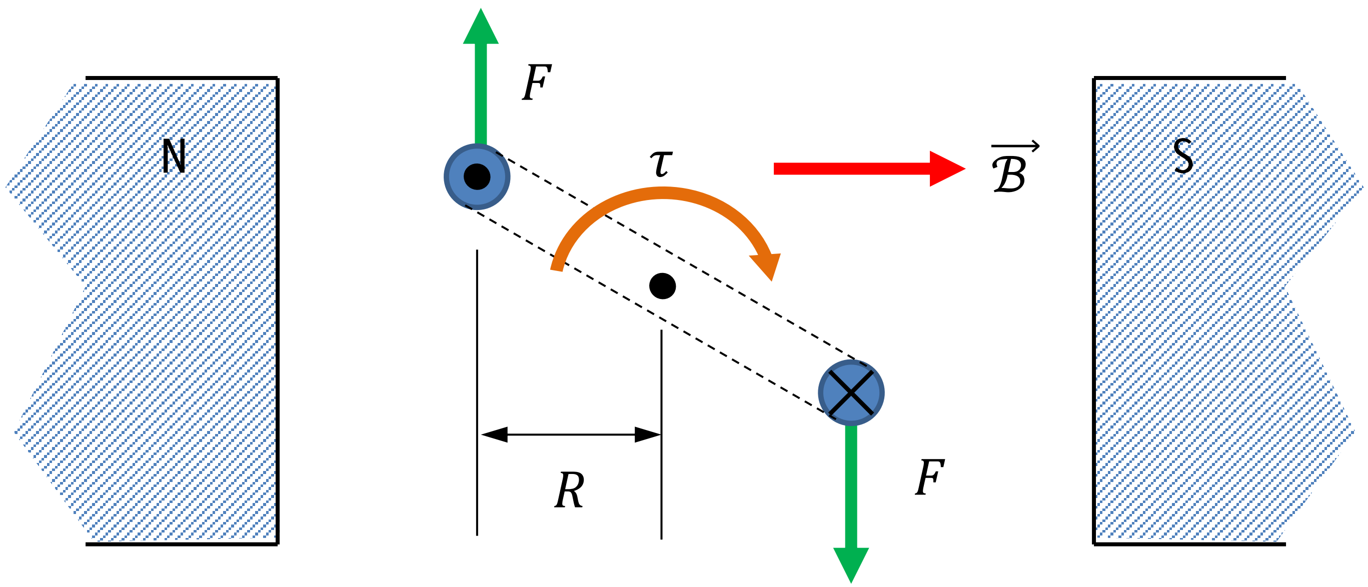
20	Thermal resistance rotor-housing	K / W				3.1					
21	Thermal time constant winding	s				12					

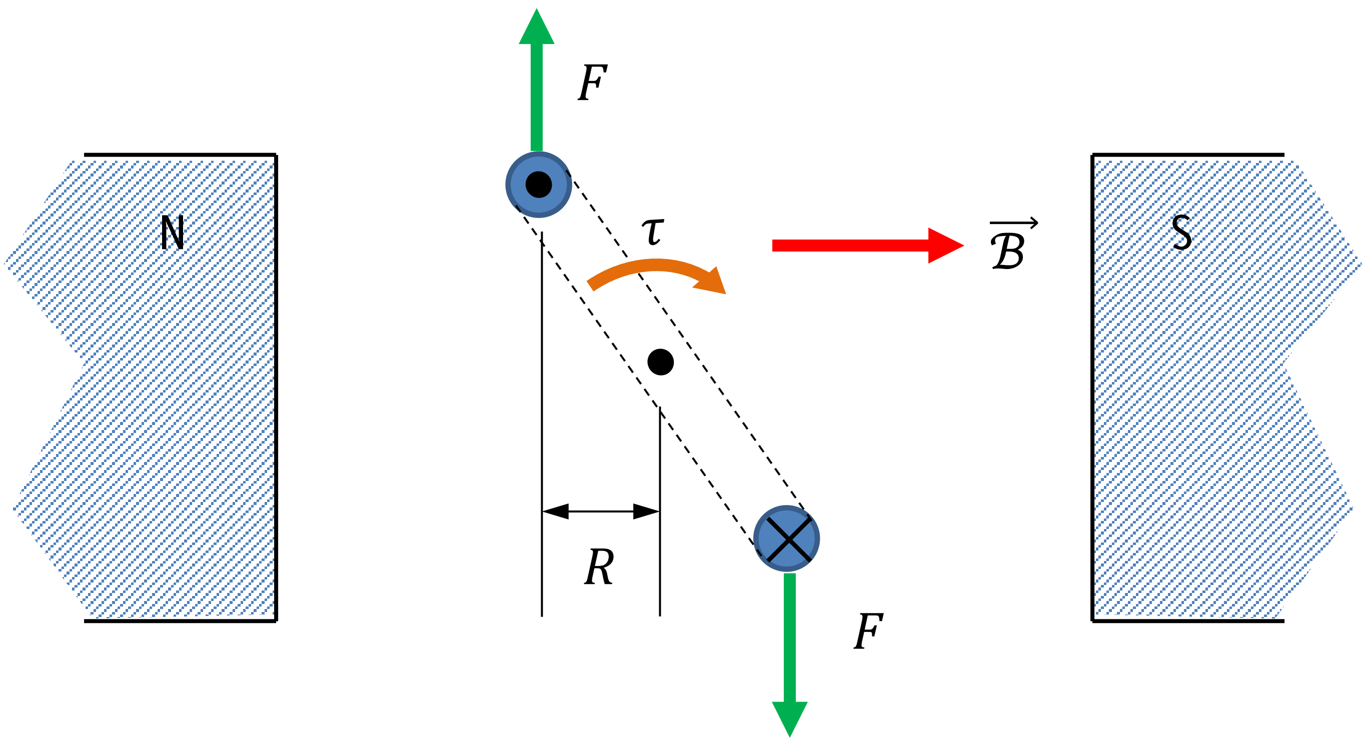
TORQUE RESULTS FROM FORCE APPLIED ABOUT A CENTER AXIS

- If the magnetic field $\vec{\mathcal{B}}$ is stationary, and the winding rotates, then moment arm R keeps getting shorter…



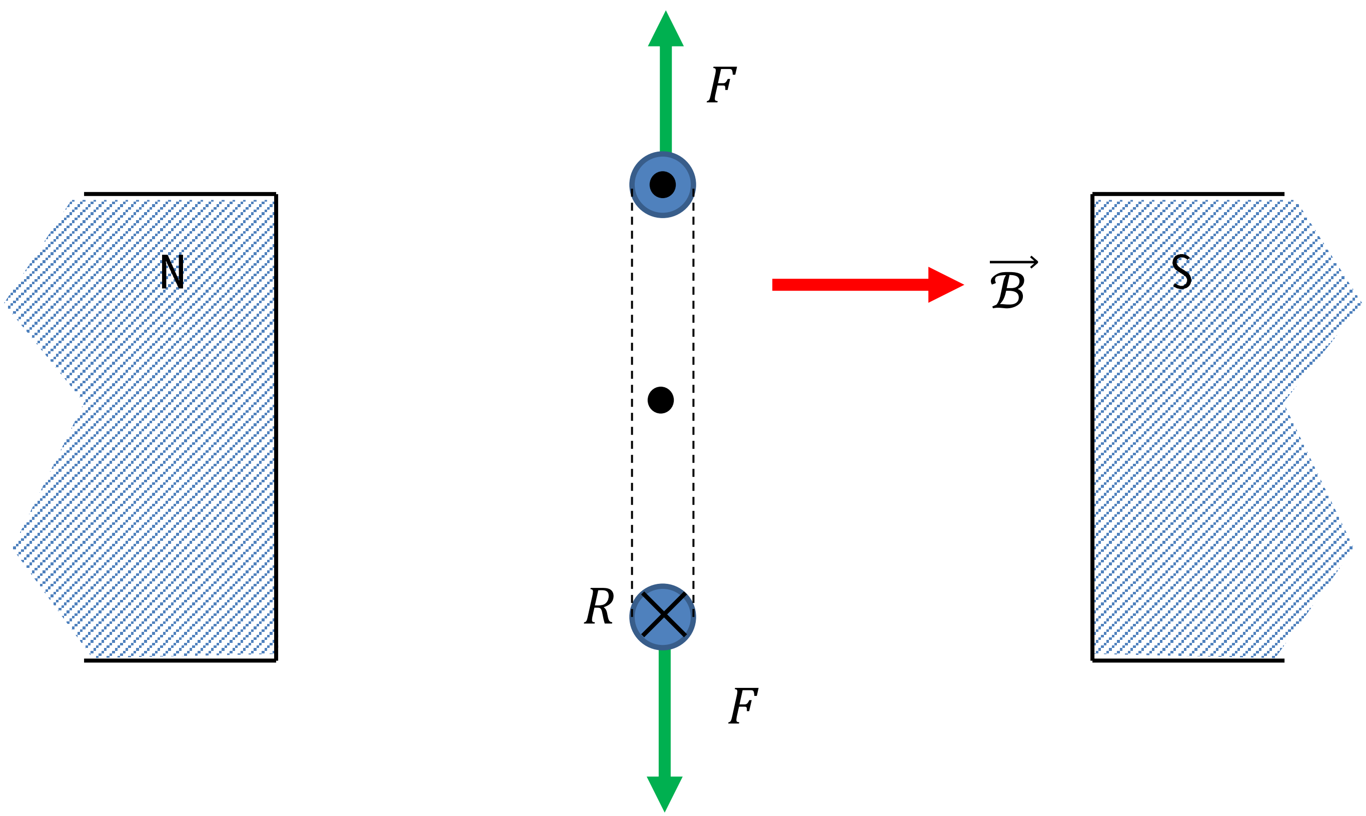
TORQUE RESULTS FROM FORCE APPLIED ABOUT A CENTER AXIS

- … and the torque keeps getting smaller …



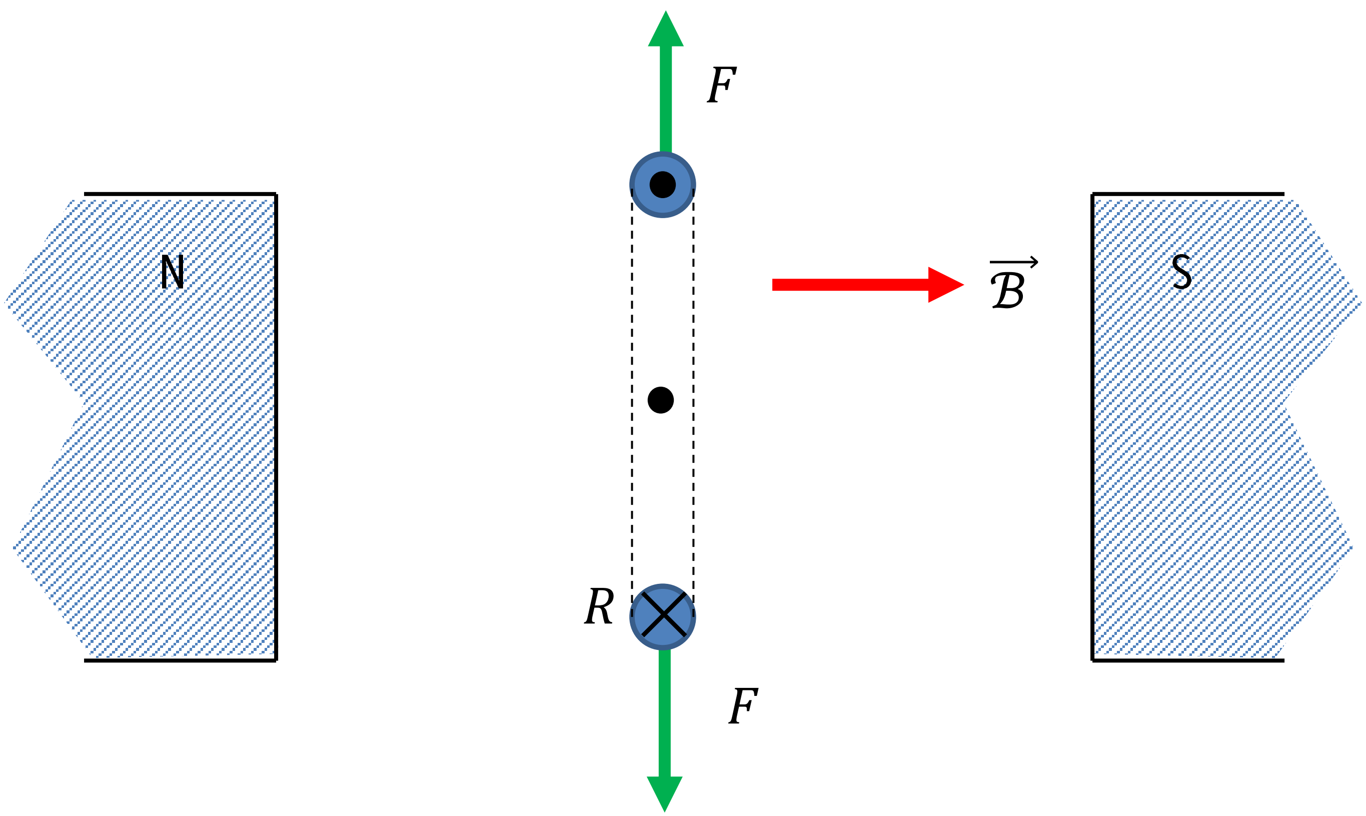
TORQUE RESULTS FROM FORCE APPLIED ABOUT A CENTER AXIS

- … until the moment arm disappears completely and we produce no torque at all.



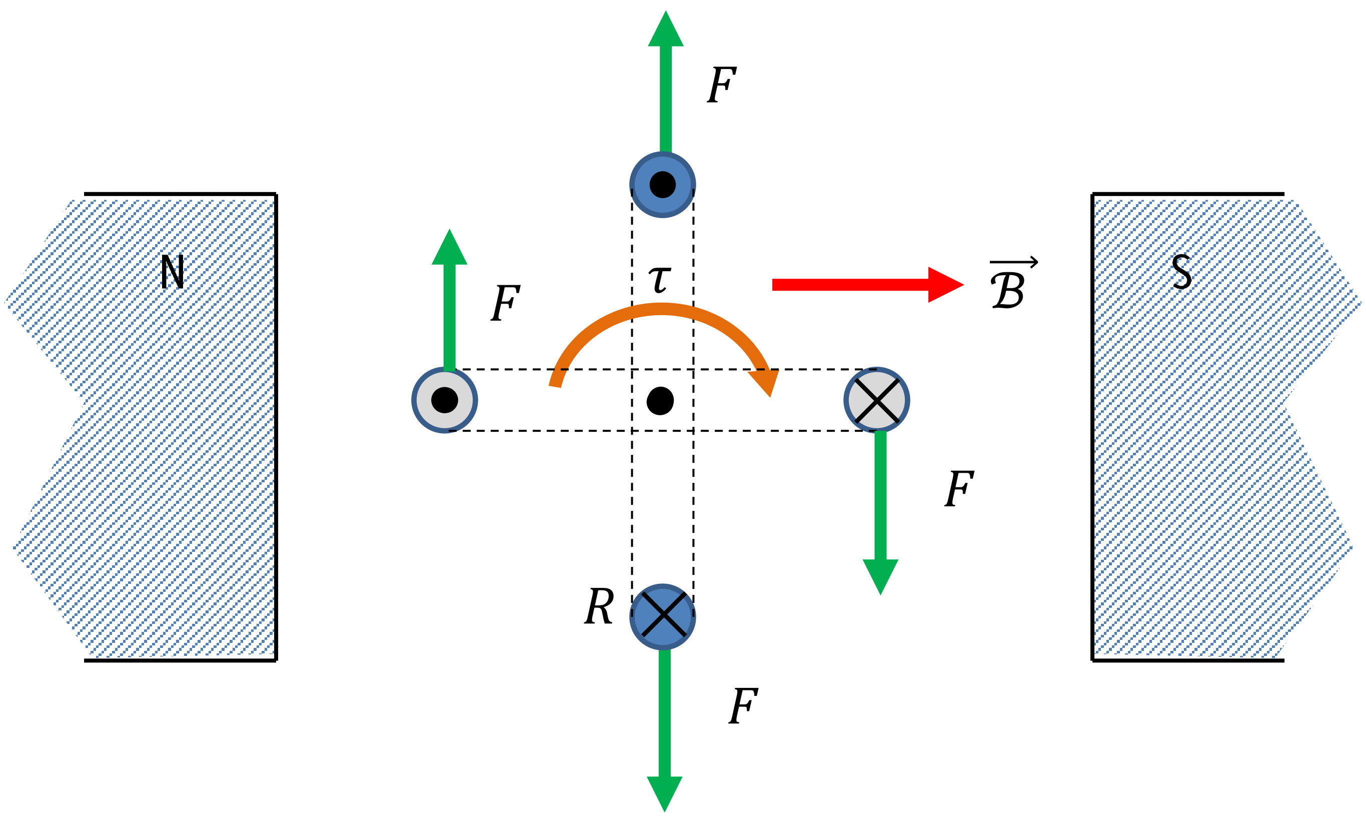
TORQUE RESULTS FROM FORCE APPLIED ABOUT A CENTER AXIS

- What shall we do?



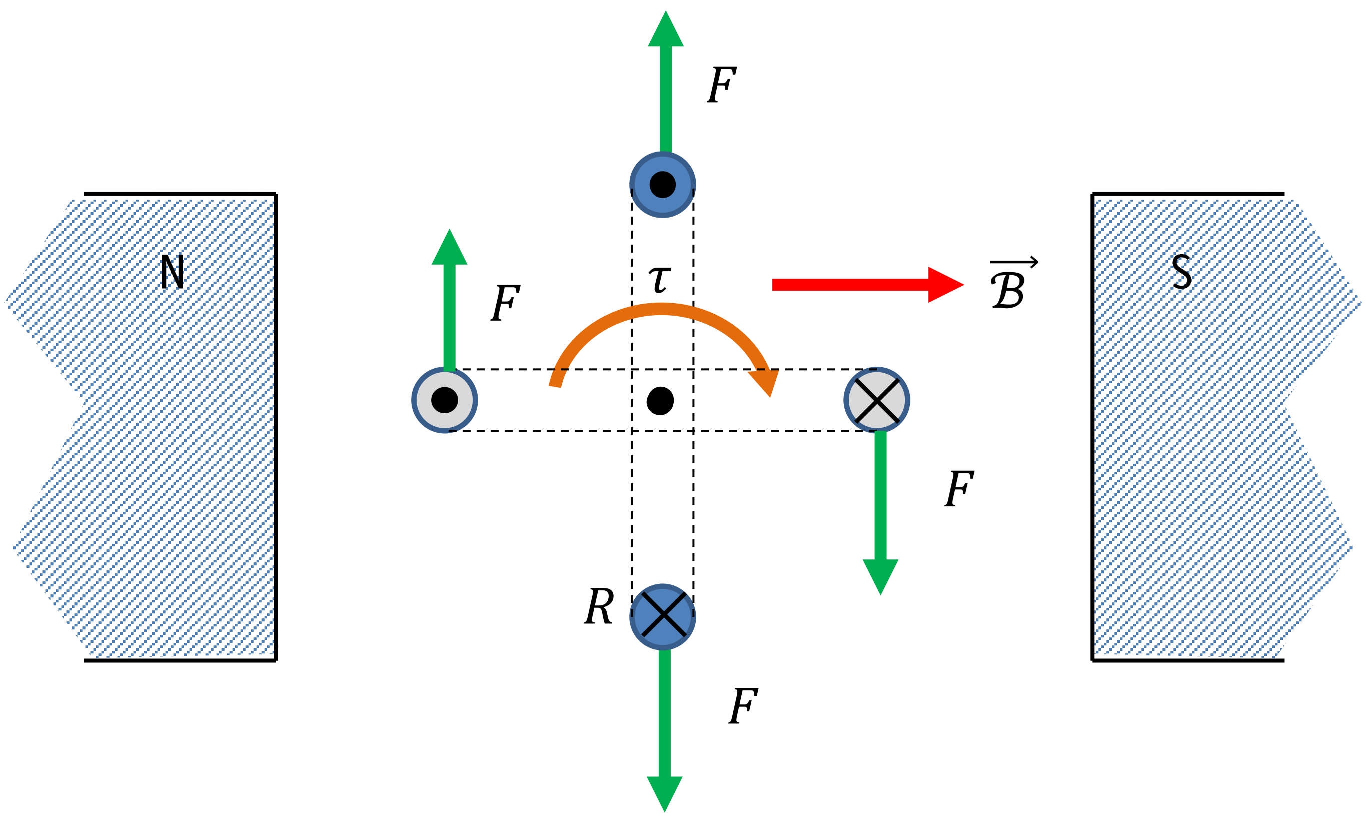
TORQUE RESULTS FROM FORCE APPLIED ABOUT A CENTER AXIS

- What about a second winding?



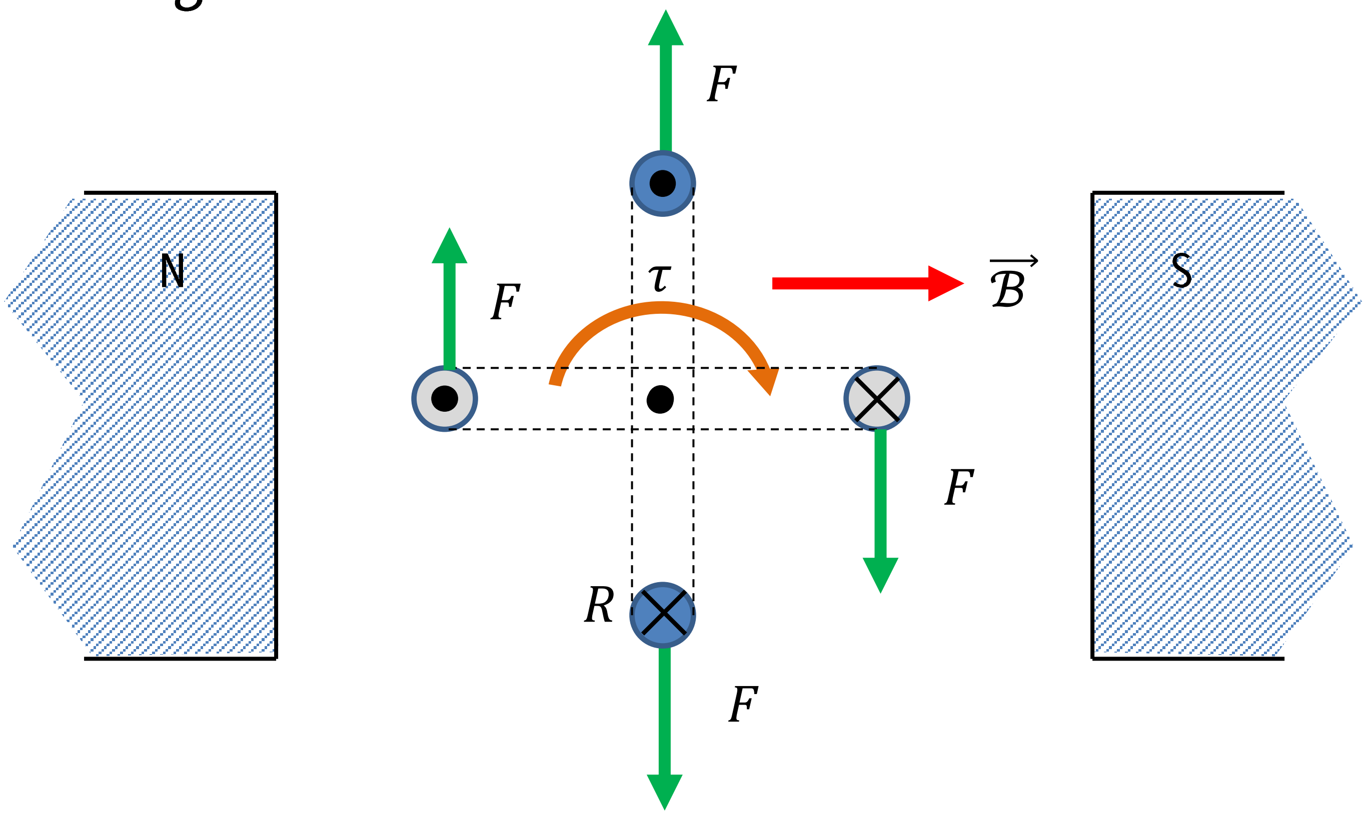
TORQUE RESULTS FROM FORCE APPLIED ABOUT A CENTER AXIS

- Do we need current in the first winding, if it's not producing any torque?



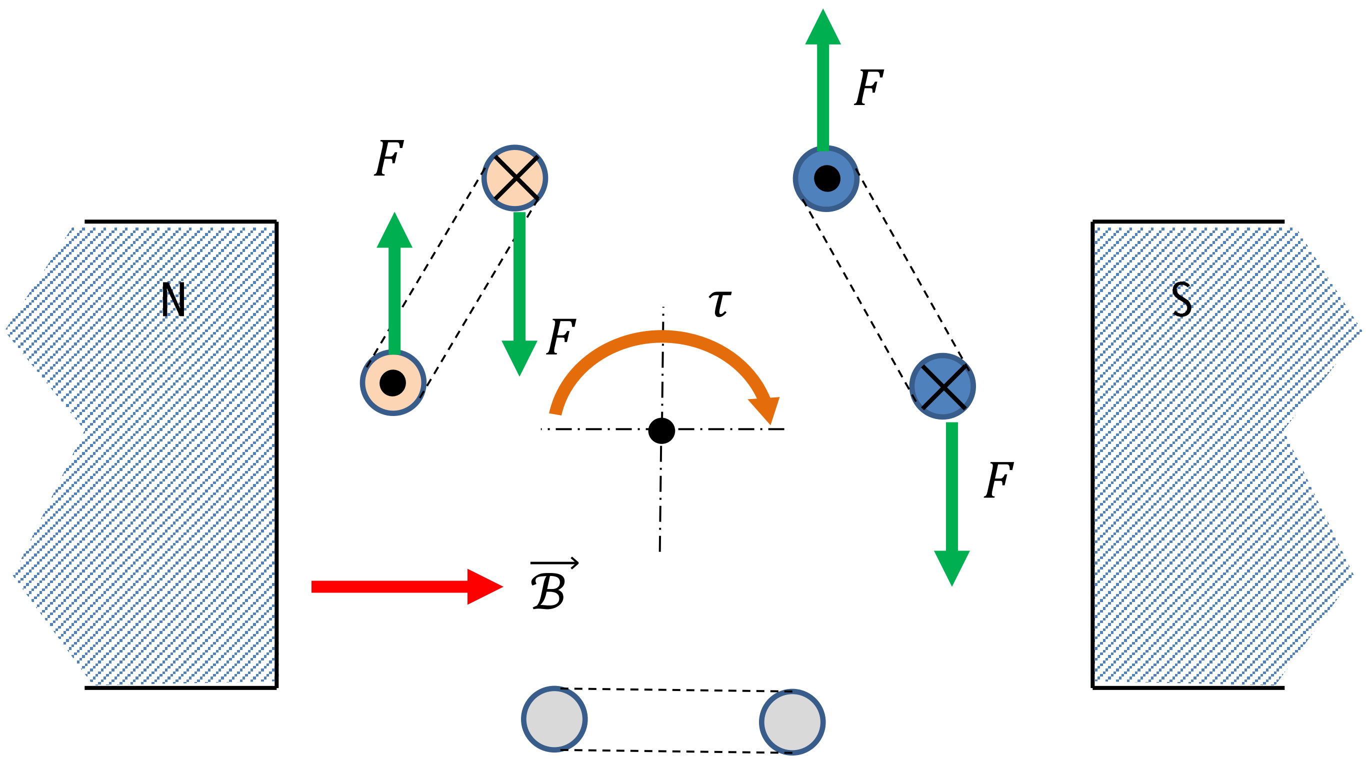
TORQUE RESULTS FROM FORCE APPLIED ABOUT A CENTER AXIS

- So in addition to a magnetic field and electric current, we need a means for switching current between windings! Such a device is called a ***commutator***.



TORQUE RESULTS FROM FORCE APPLIED ABOUT A CENTER AXIS

- To make it easier to construct the motor, we offset the windings, and selectively apply current.



3-pole PMDC motor

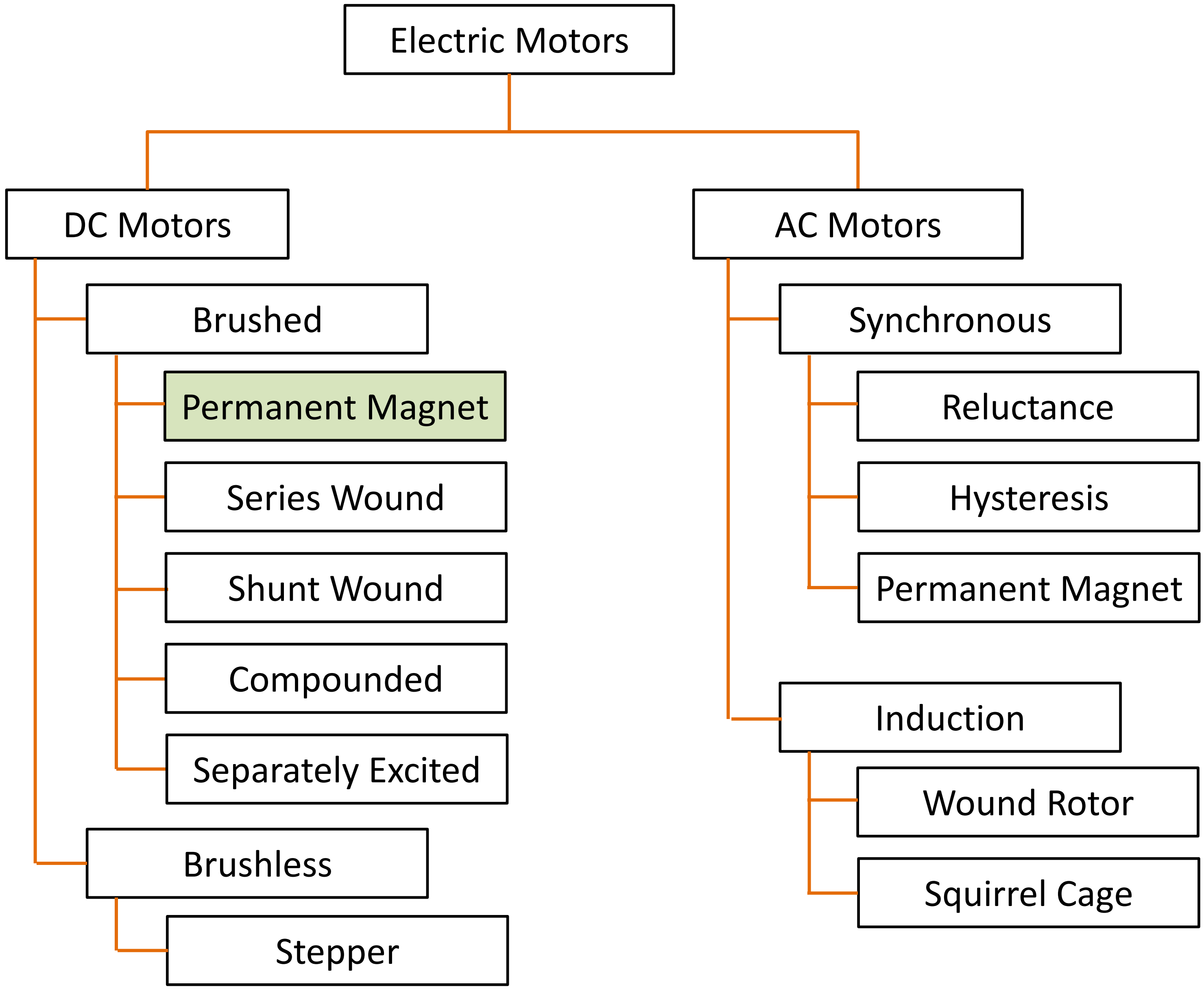
TWO CATEGORIES OF DC MOTORS

1. Brushed (or brush-type)
2. Brushless

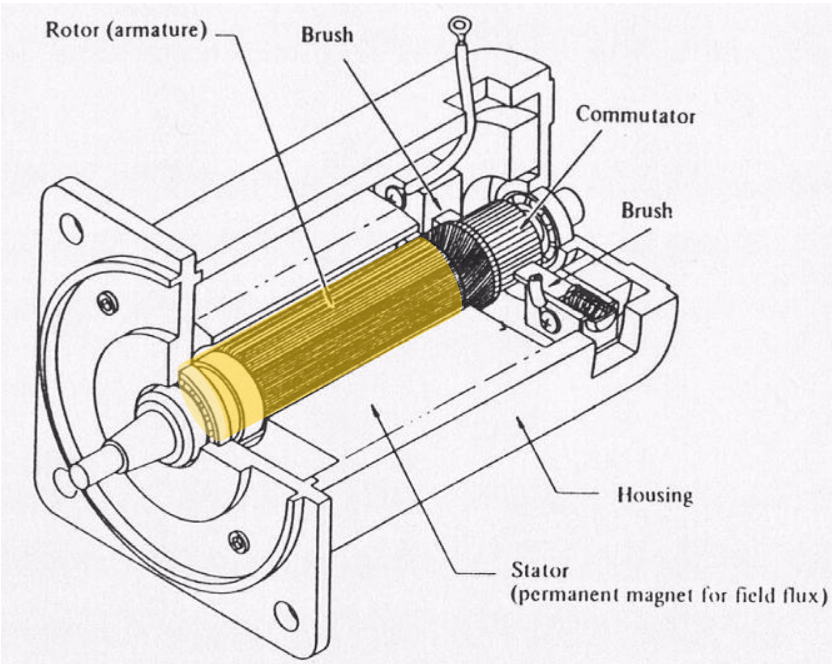
- Difference is in how we ***commutate*** (switch current through) the windings

- We begin by examining brushed, permanent-magnet direct-current (PMDC) motors, as they are inexpensive, widely available, and utilize operating principles that are relatively easy to understand

ELECTRIC MOTORS



DC MOTOR TERMINOLOGY



Motors are actuation devices (actuators) that generate ***torque***.

Mechanical Terms

- **Rotor**: rotating part of the motor.
- **Stator**: stationary part of the motor.
- **Commutator**: part of rotor in contact with the brushes
- **Brushes**: part of electrical circuit through which current is supplied to armature.

ROTOR

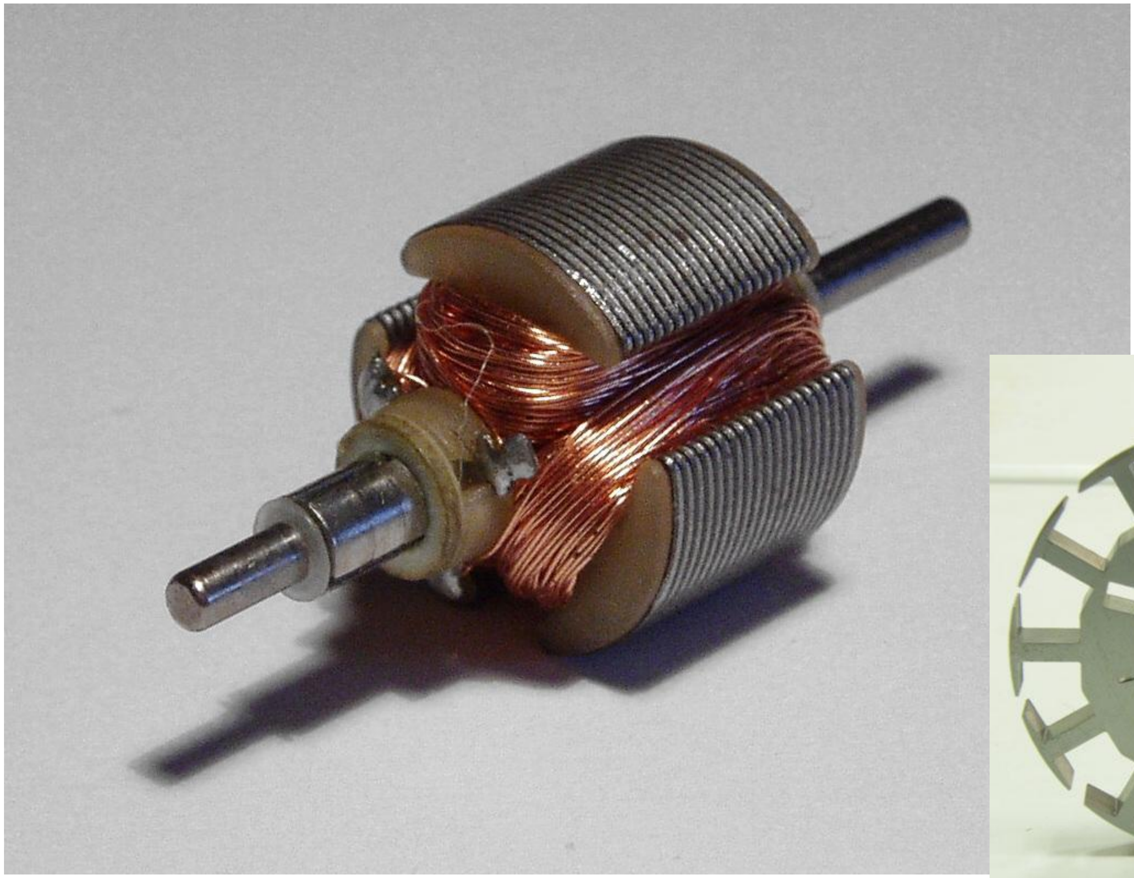
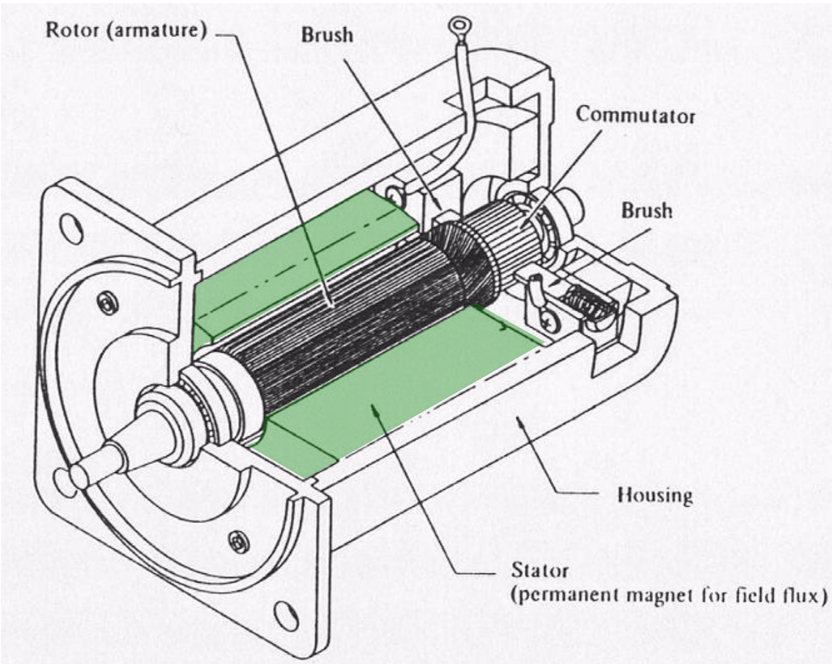


Image: https://en.wikipedia.org/wiki/File:Electric_Motor_Rotor.jpg
http://motorcorechina.com

DC MOTOR TERMINOLOGY



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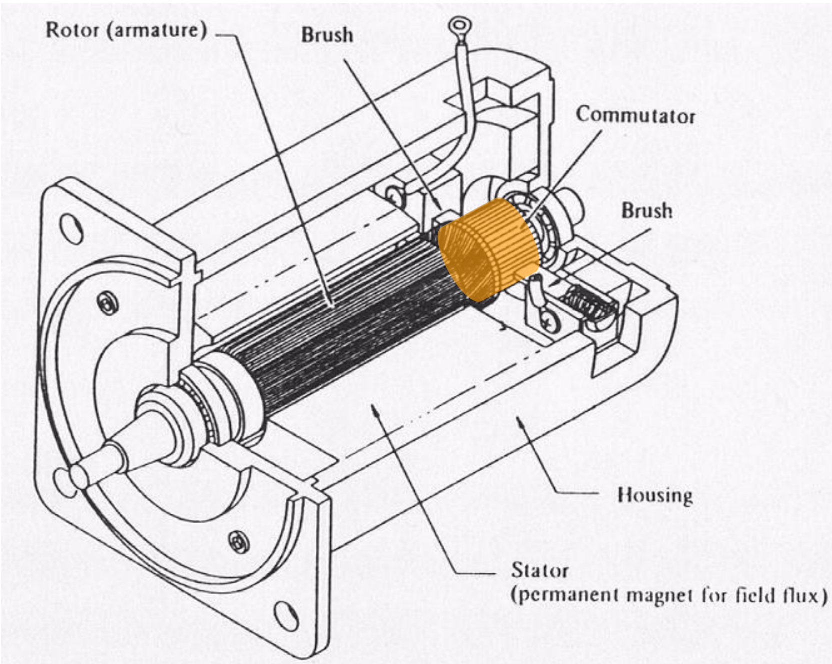
STATOR

Images: http://static.howstuffworks.com/gif/motor8.jpg
http://www.johnsonelectric.com/common/en/images/resources-for-engineers/automotive-applications/motion-technology/pmdc-motor/basic-configuration-04.jpg

DC MOTOR TERMINOLOGY



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COMMUTATOR

Commutation

- To reverse the direction of current flow, or to take current out of one circuit, and apply it to a different circuit

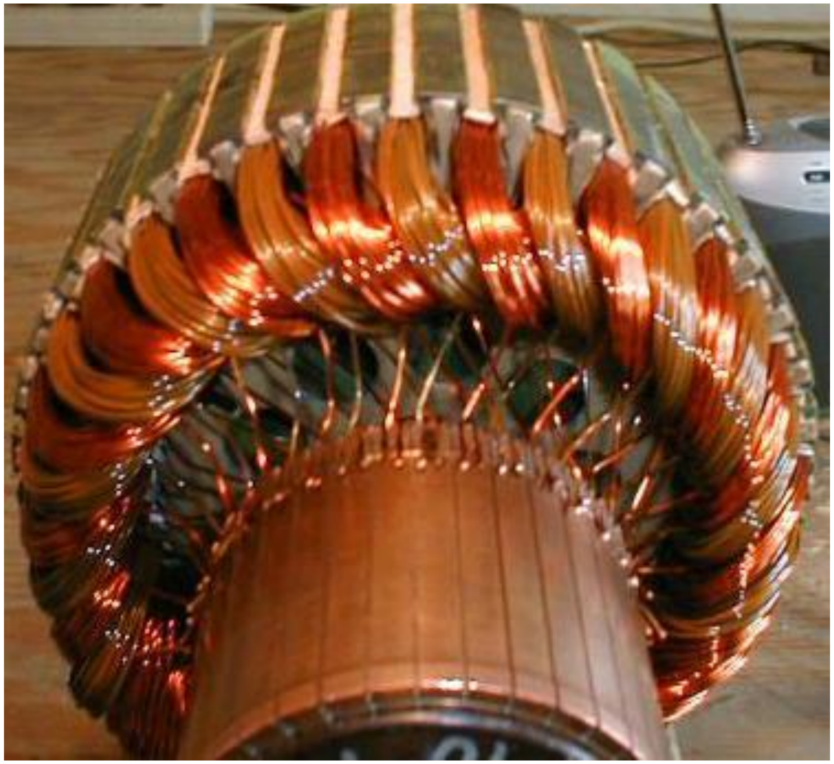
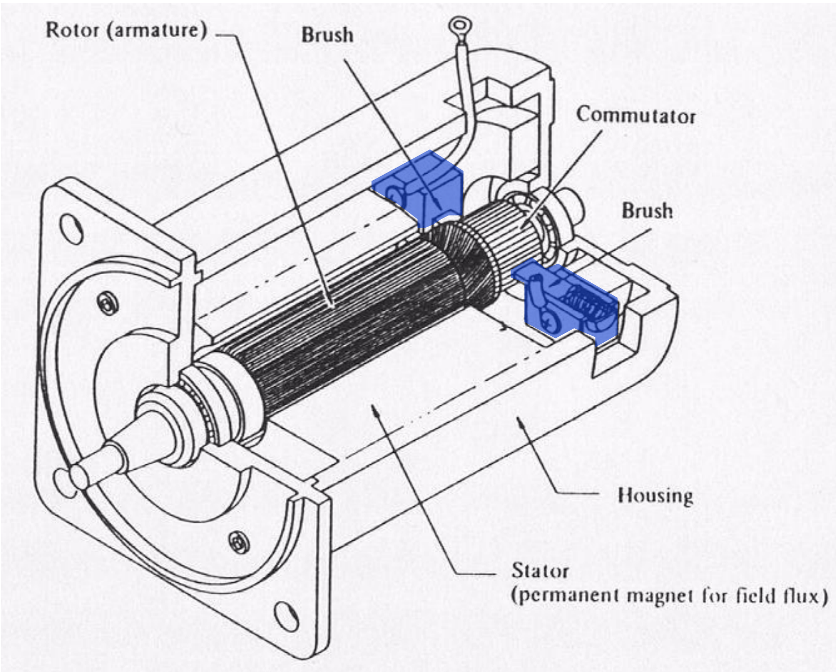


Image: http://www.daviddarling.info/encyclopedia/C/commutator.html

DC MOTOR TERMINOLOGY



Motors are actuation devices (actuators) that generate ***torque***.

Mechanical Terms

- **Rotor**: rotating part of the motor.
- **Stator**: stationary part of the motor.
- **Commutator**: part of rotor in contact with the brushes
- **Brushes**: part of electrical circuit through which current is supplied to armature.

COMMUTATOR AND BRUSHES

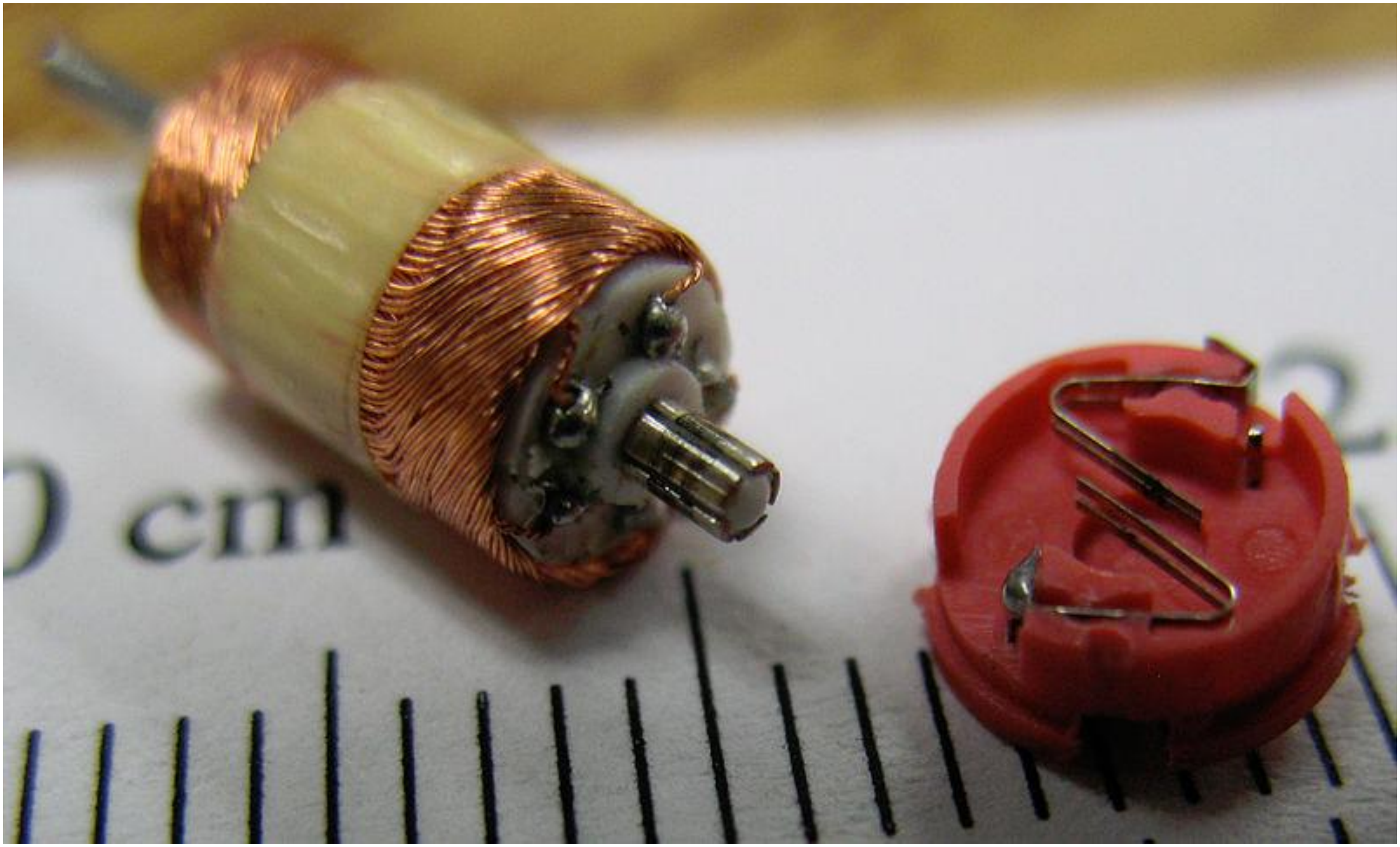
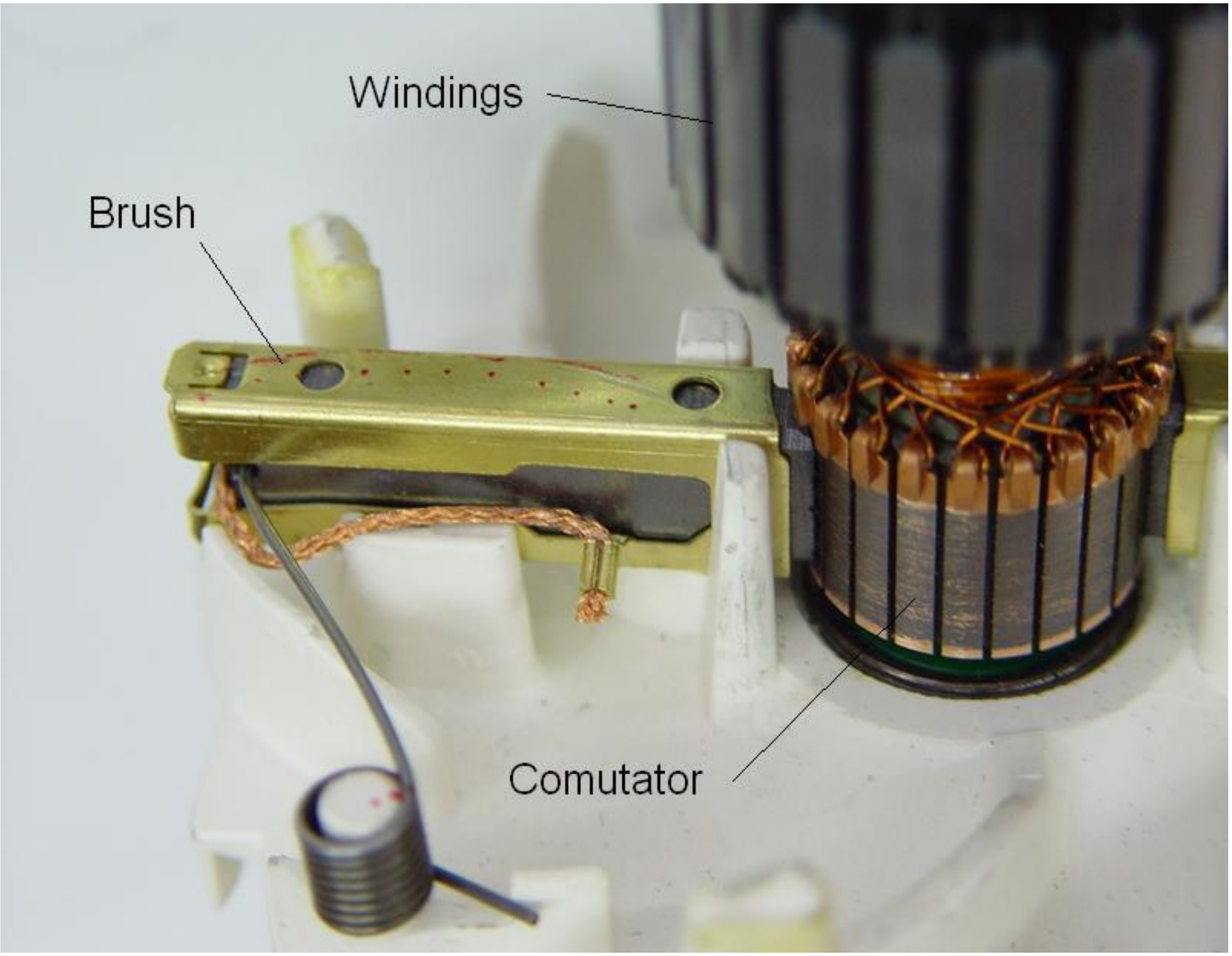
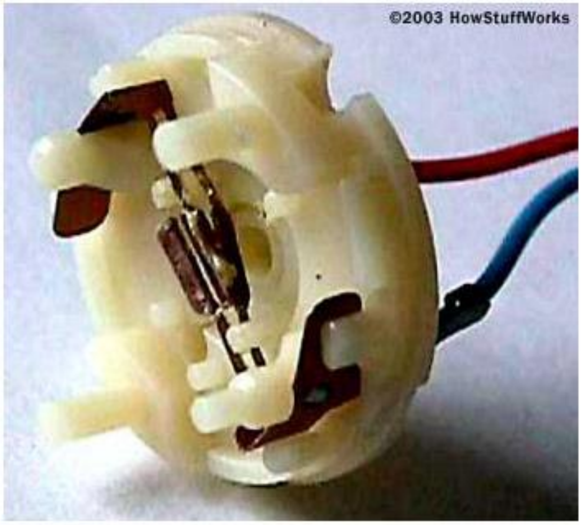


Image: https://en.wikipedia.org/wiki/File:Tiny_motor_windings_-_commutator_-_brushes_in_Zip_Zaps_toy_R-C_car.jpg

BRUSHES



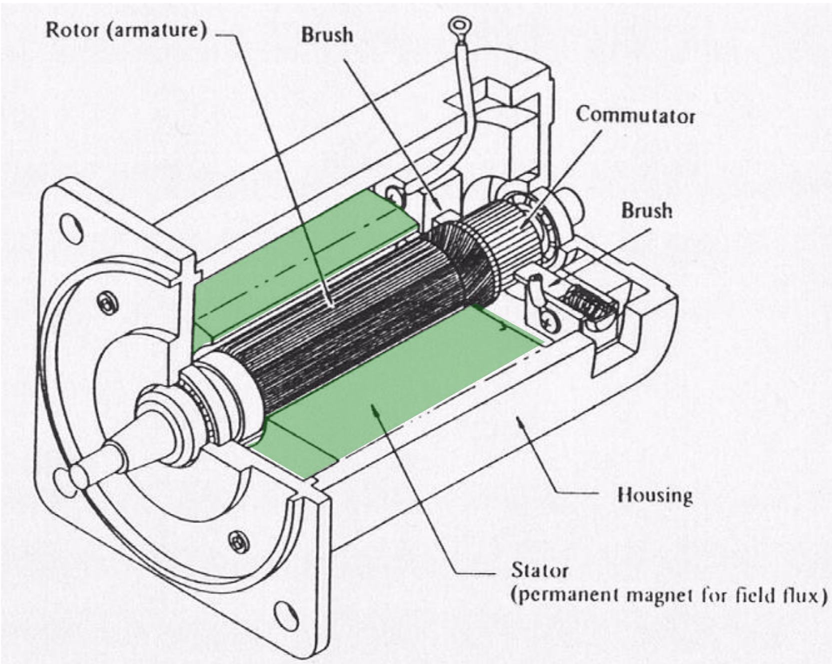


BRUSHES ARE A WEAK POINT FOR BRUSHED DC MOTORS

Brushes tend to:

- Wear out
- Generate electrical (and acoustic) noise
  - Copper-graphite (cheaper, more current, more noise)
  - Precious metal (more expensive, less current, less noise)
- Limit maximum voltage

DC MOTOR TERMINOLOGY

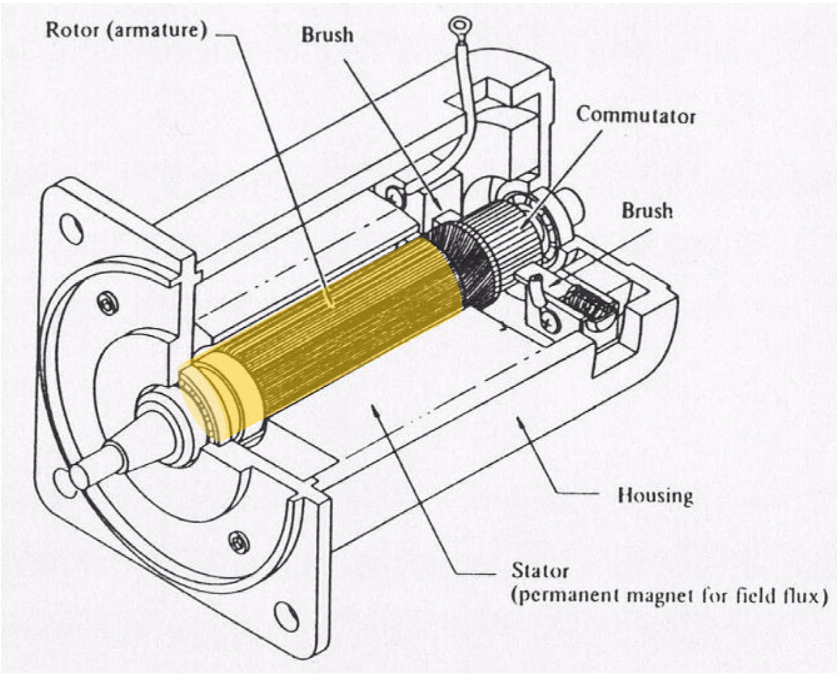


Motors are actuation devices (actuators) that generate ***torque***.

Electrical Terms

- **Field System**: the part of the motor that provides the magnetic flux.
- **Armature**: the current-carrying part of the motor that interacts with the magnetic flux to produce torque.

DC MOTOR TERMINOLOGY



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- **Field System**: the part of the motor that provides the magnetic flux.
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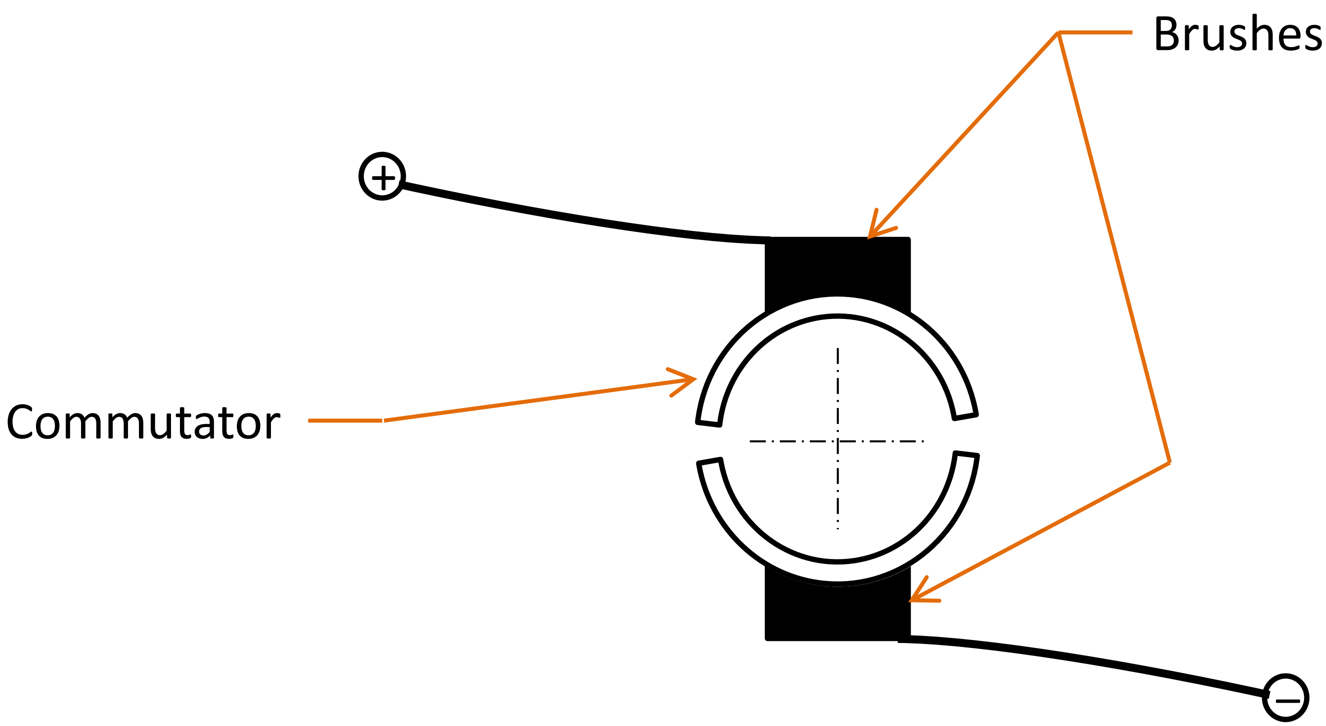
COMMUTATION

- To keep torque from reversing, the commutator changes current direction at point where torque is zero. This effect is achieved with *brushes*.



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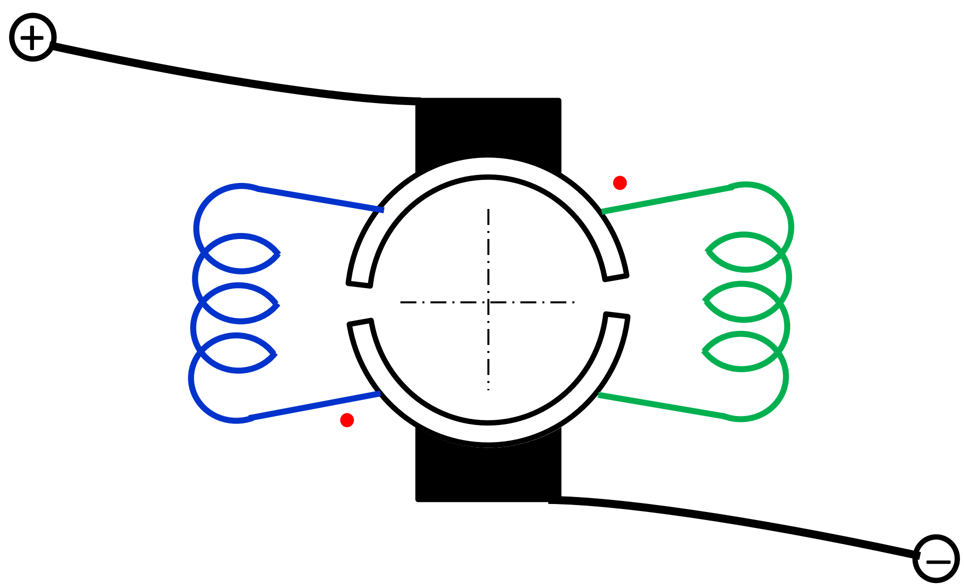

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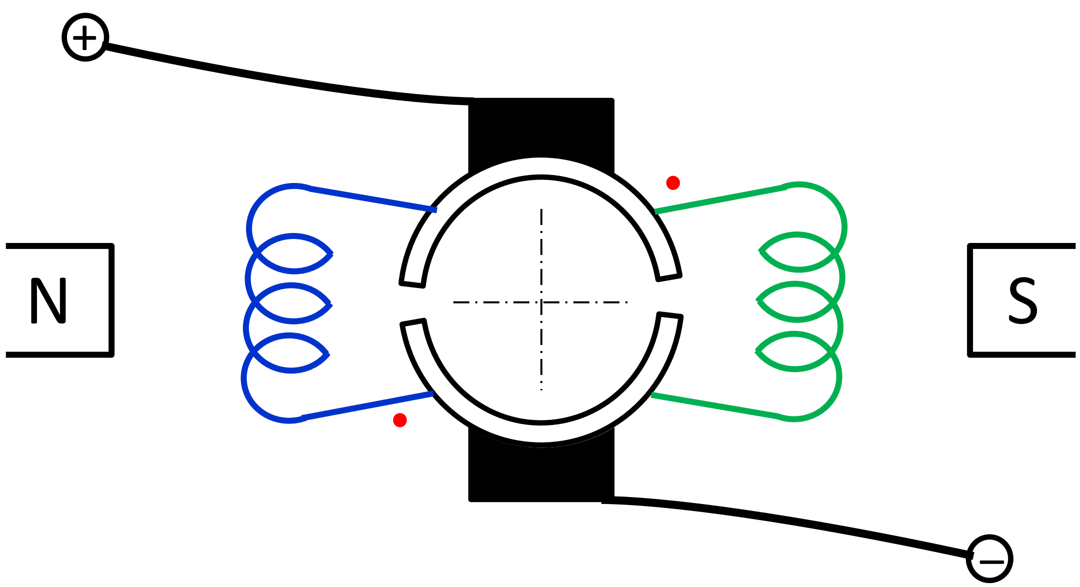

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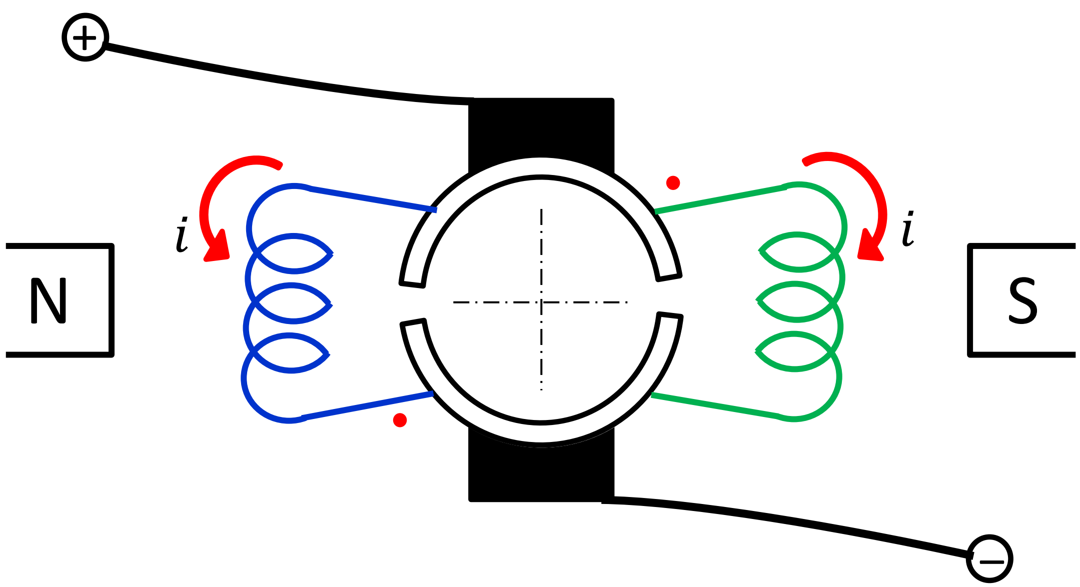

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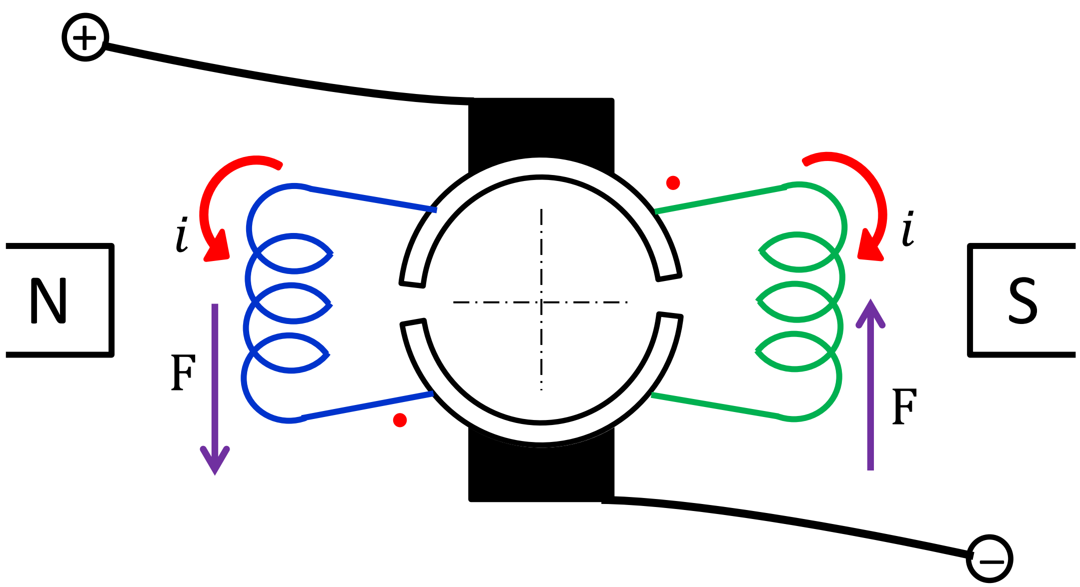

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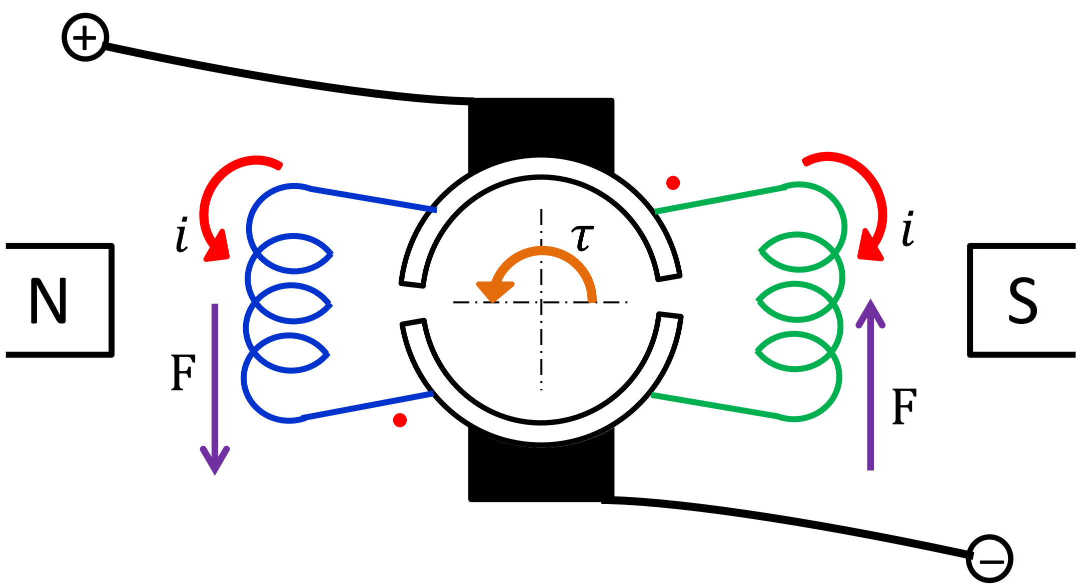

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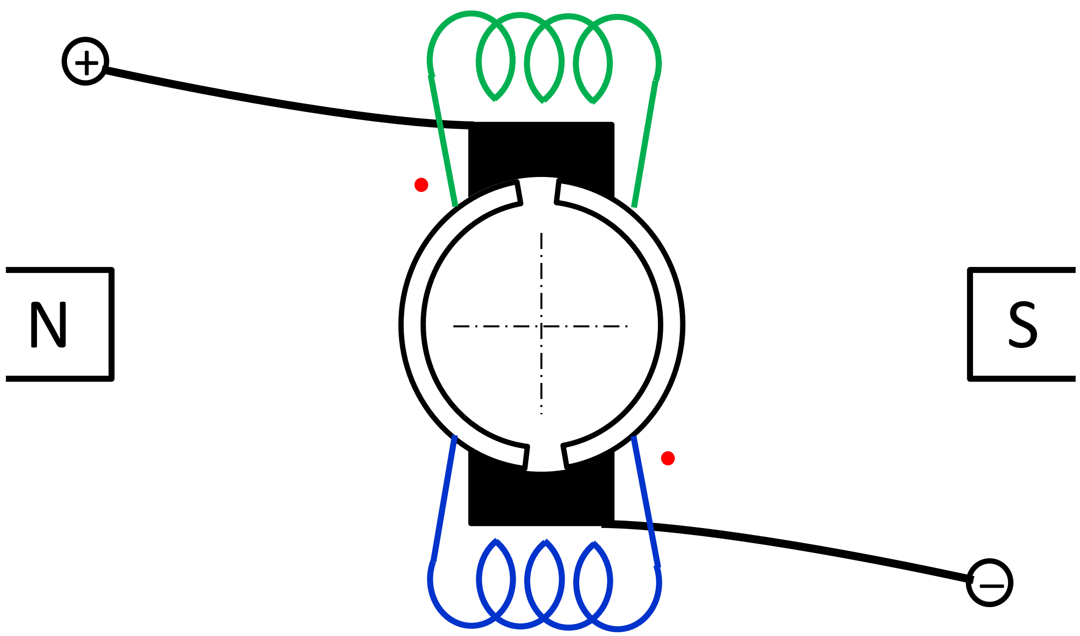

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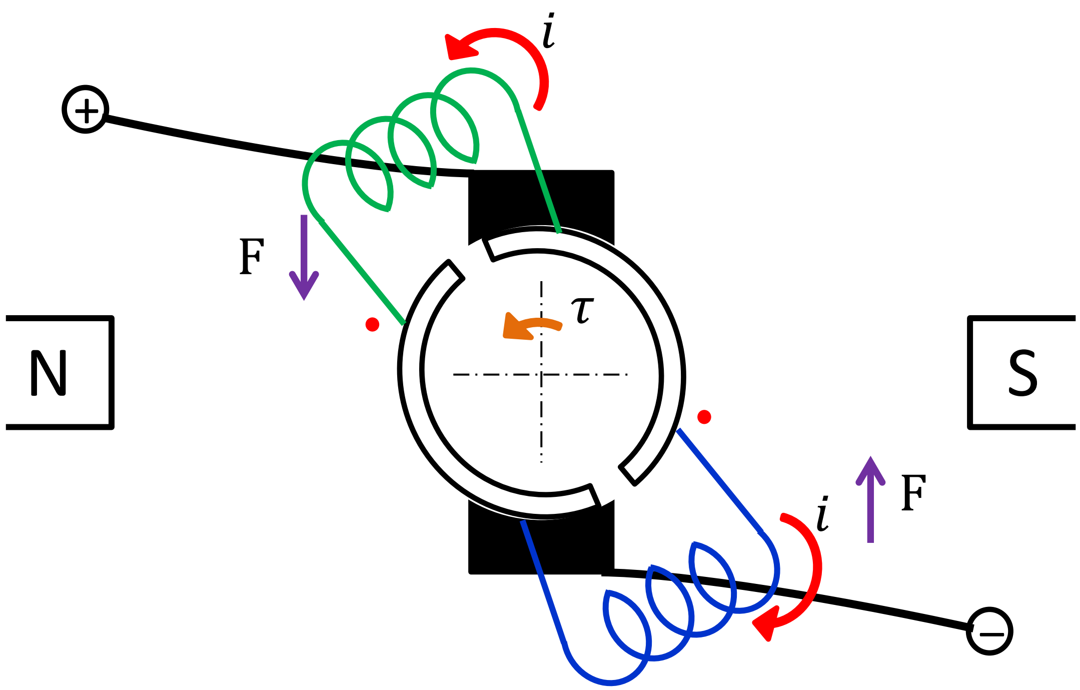

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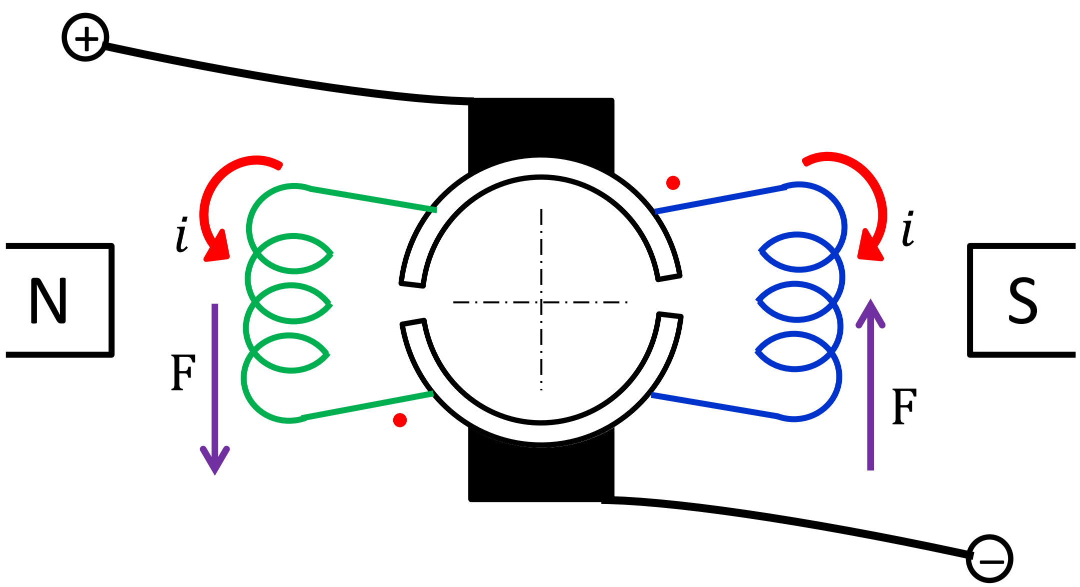
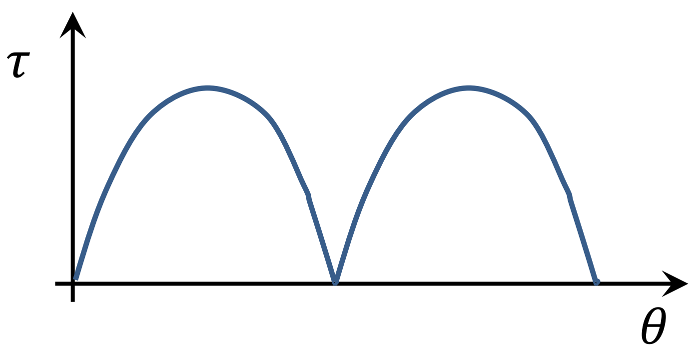
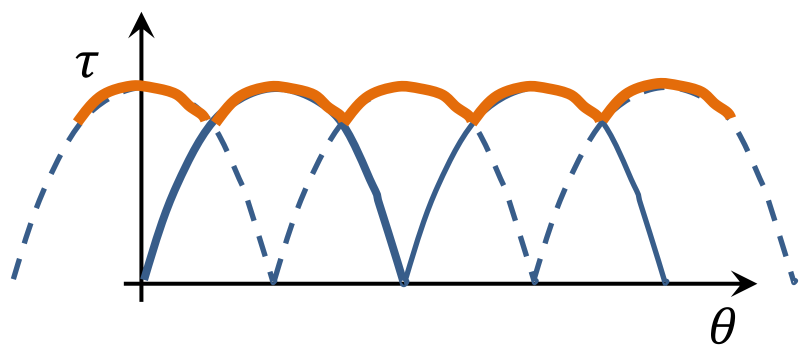


COMMUTATION

- Brush commutation amounts to a mechanical switching control system.
- To avoid top-dead-center problem and make more uniform torque generation, multi-coil rotors are always used.



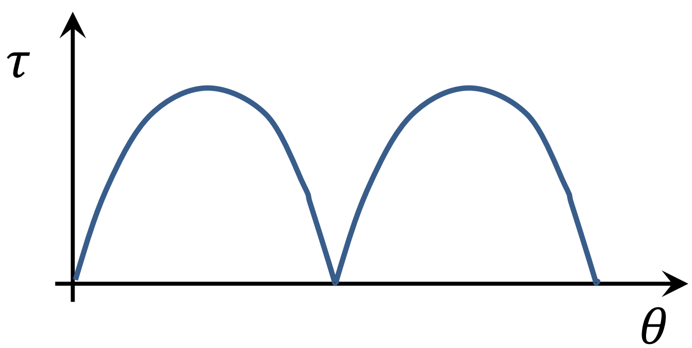
Single Phase, Two Pole



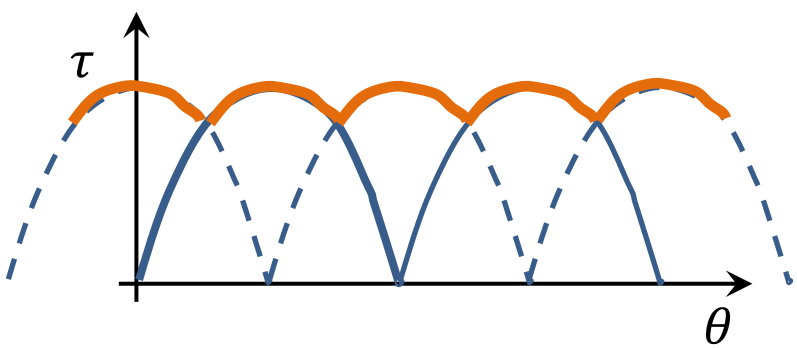
Two Phase, Four Pole

COMMUTATION

- So within the bounds of torque ripple, can we produce a fixed torque at all operating speeds with a PMDC motor?



Single Phase, Two Pole

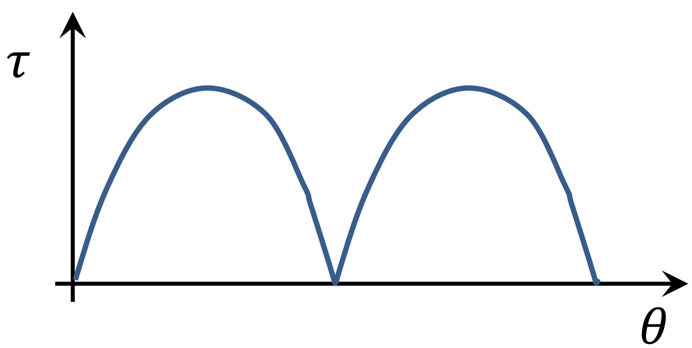


Two Phase, Four Pole

COMMUTATION

- So within the bounds of torque ripple, can we produce a fixed torque at all operating speeds with a PMDC motor?

Unfortunately, NO!



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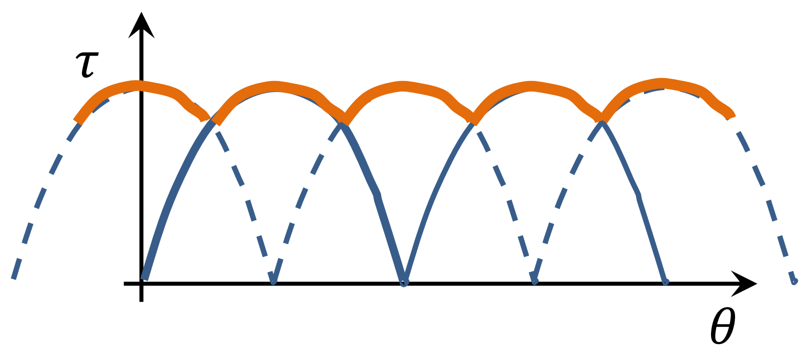
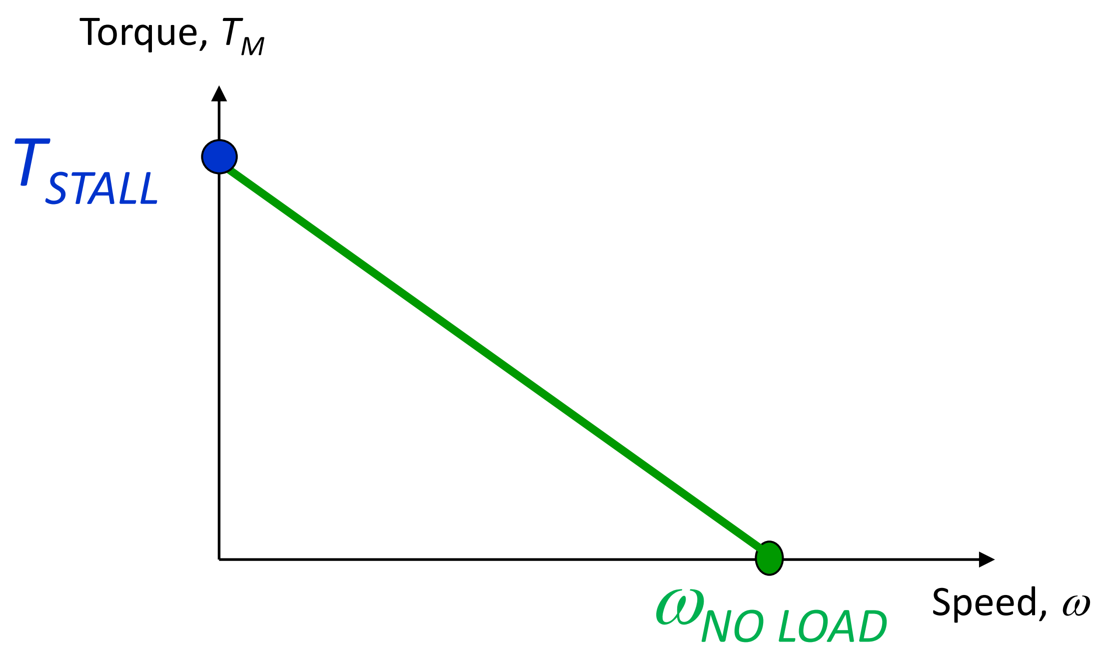


Two Phase, Four Pole

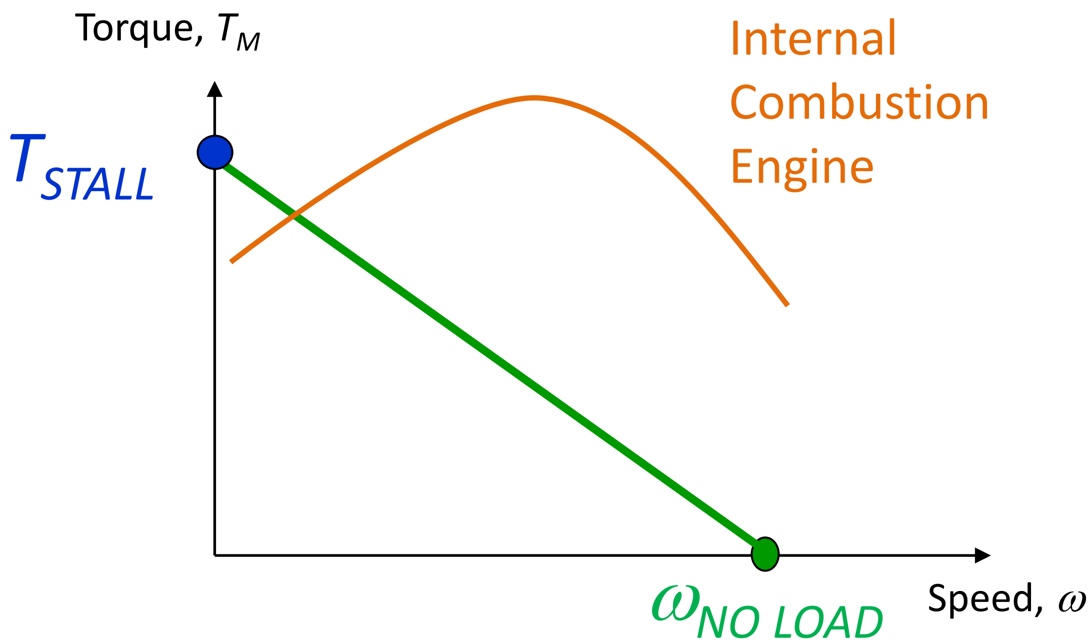
TORQUE AND SPEED ARE LINEARLY RELATED FOR A PMDC MOTOR

We'll show why this is the case in a few slides…

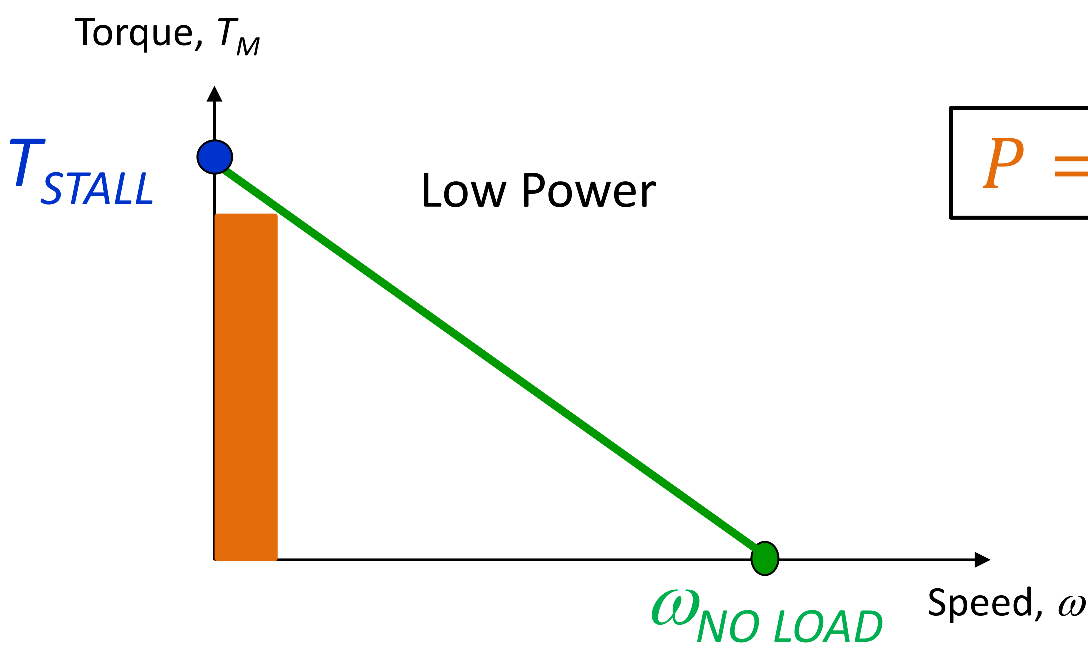


TORQUE AND SPEED ARE LINEARLY RELATED FOR A PMDC MOTOR

Other actuators have very different speed/torque curves

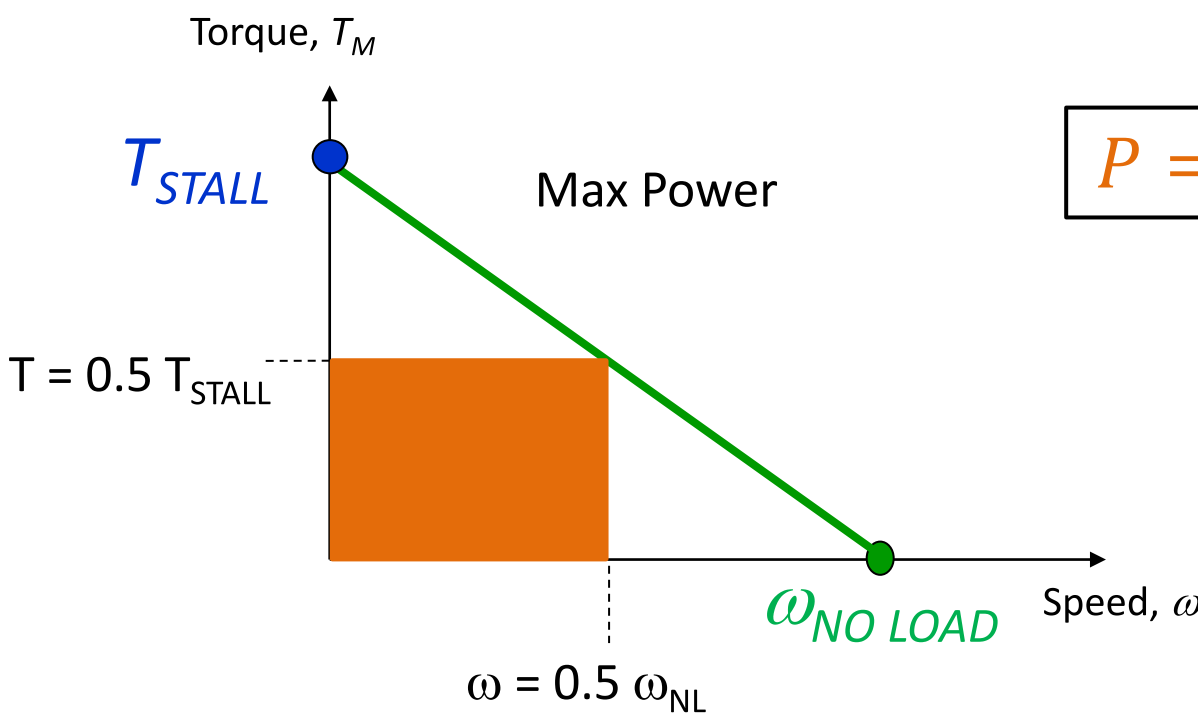


AT LOW SPEEDS, A PMDC MOTOR PRODUCES LITTLE POWER



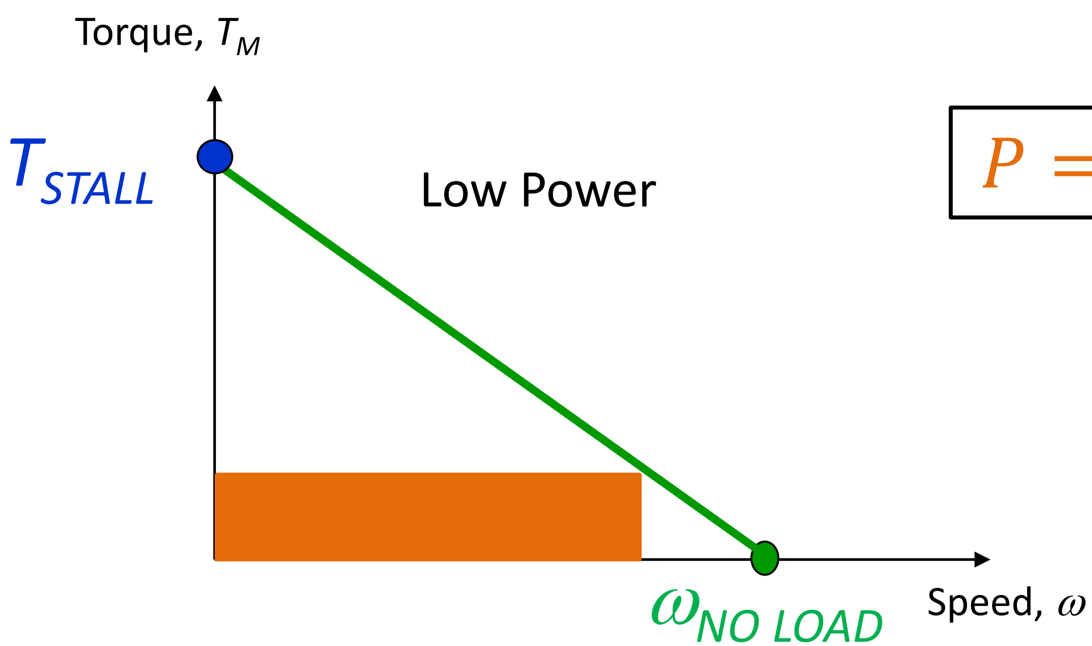
$$P = \tau \cdot \omega$$

AT MID-RANGE SPEEDS, A PMDC MOTOR PRODUCES MAX POWER



$$P = \tau \cdot \omega$$

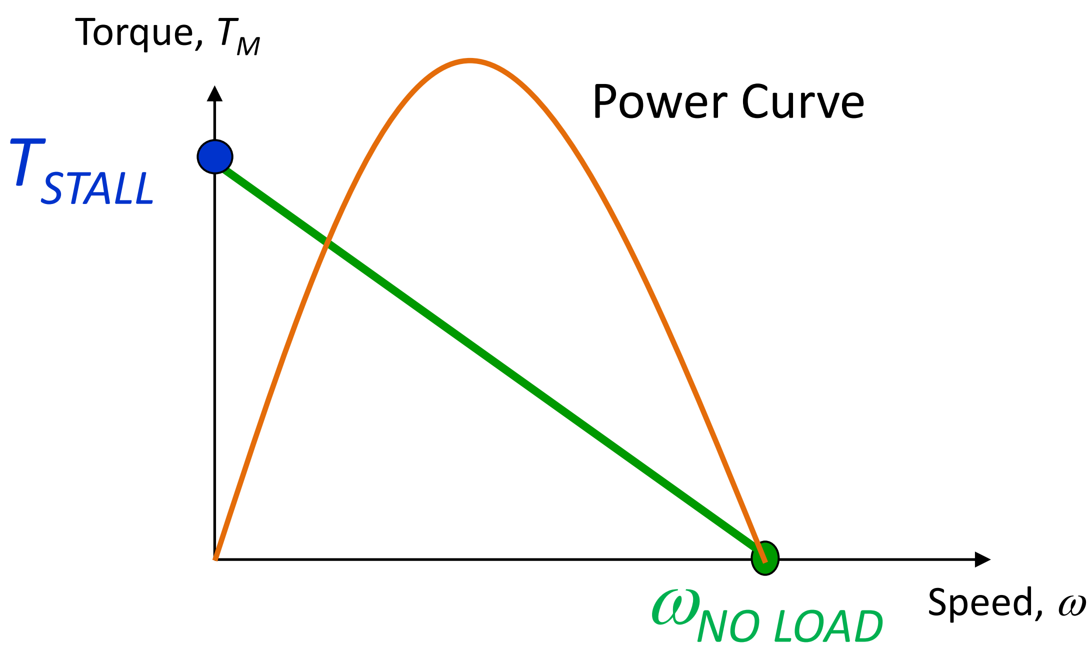
AT HIGH SPEED, A PMDC MOTOR PRODUCES LITTLE POWER



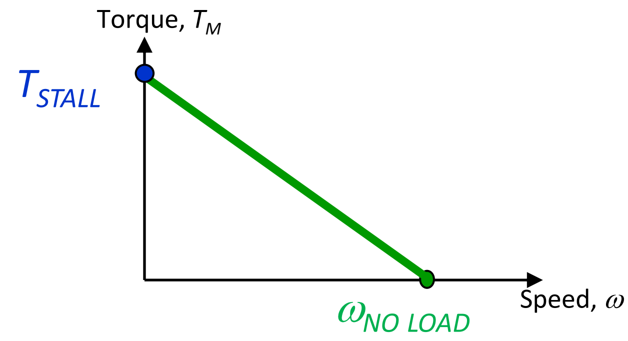
$$P = \tau \cdot \omega$$

MAX POWER IS ACHIEVED AT HALF OF NO-LOAD SPEED

Important to remember if you want to optimize your vehicle's acceleration!



DC MOTOR SPECIFICATIONS



	Motor Data		118749	118750	118751	118752	118753	118754	118755	118756	118757
1	Assigned power rating	W				20					
2	Nominal voltage	Volt				24.0					
3	No load speed	rpm				9660					
4	Stall torque	mNm				240					
5	Speed / torque gradient	rpm / mNm				41.2					
6	No load current	mA				37					
7	Starting current	mA				10300					
8	Terminal resistance	Ohm				2.32					
9	Max. permissible speed	rpm				11000					
10	Max. continuous current	mA				1230					
11	Max. continuous torque	mNm				28.4					
12	Max. power output at nominal voltage	mW				58400					
13	Max. efficiency	%				85					
14	Torque constant	mNm / A				23.2					
15	Speed constant	rpm / V				412					
16	Mechanical time constant	ms				5					
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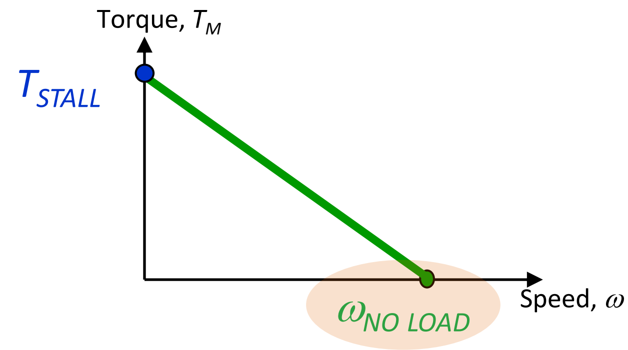
19	Thermal resistance housing-ambient	K / W				14					
20	Thermal resistance rotor-housing	K / W				3.1					
21	Thermal time constant winding	s				12					

DC MOTOR SPECIFICATIONS



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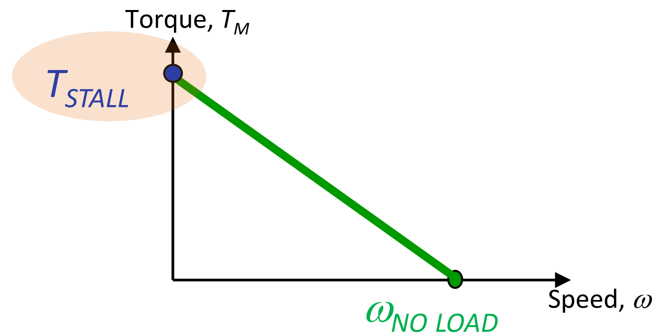
DC MOTOR SPECIFICATIONS



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DC MOTOR SPECIFICATIONS

$$T_M = K_T \cdot i_a$$

Stall torque is a test parameter, not a upper bound on the torque you should expect from your DC motor during continuous operation!

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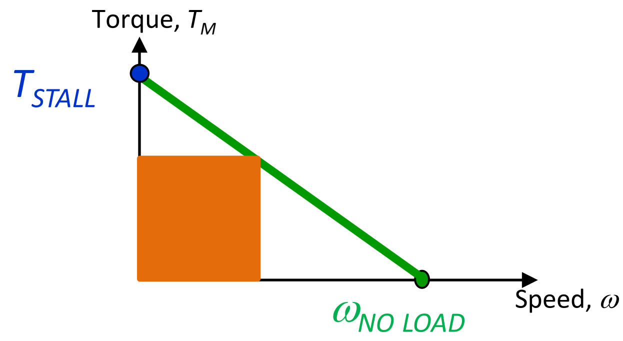
How long can you run with a stalled out motor?

Not long if you're running applying a high load torque!

DC MOTOR SPECIFICATIONS



Our theoretical peak power output is:

$$P_{max} = \left(\frac{0.240\ \mathrm{N{\cdot}m}}{2}\right)\left(\frac{9660\ \mathrm{rpm}}{2}\right)\left(\frac{\mathrm{min}}{60\ \mathrm{s}}\right)\left(\frac{2\pi\ \mathrm{rad}}{\mathrm{rev}}\right)\left(\frac{W{\cdot}s}{N{\cdot}m}\right) = 60.7\ W$$

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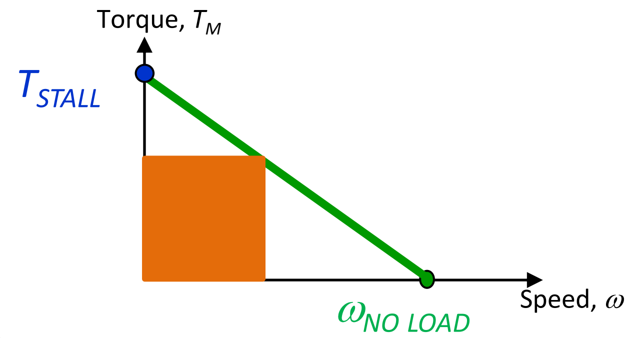
DC MOTOR SPECIFICATIONS



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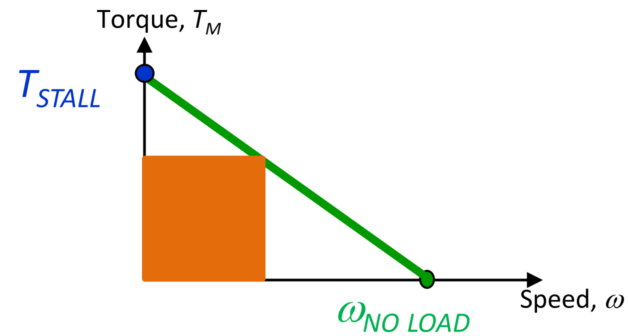
The manufacturer is being conservative in assigning a power level for ***continuous*** operation.

DC MOTOR SPECIFICATIONS



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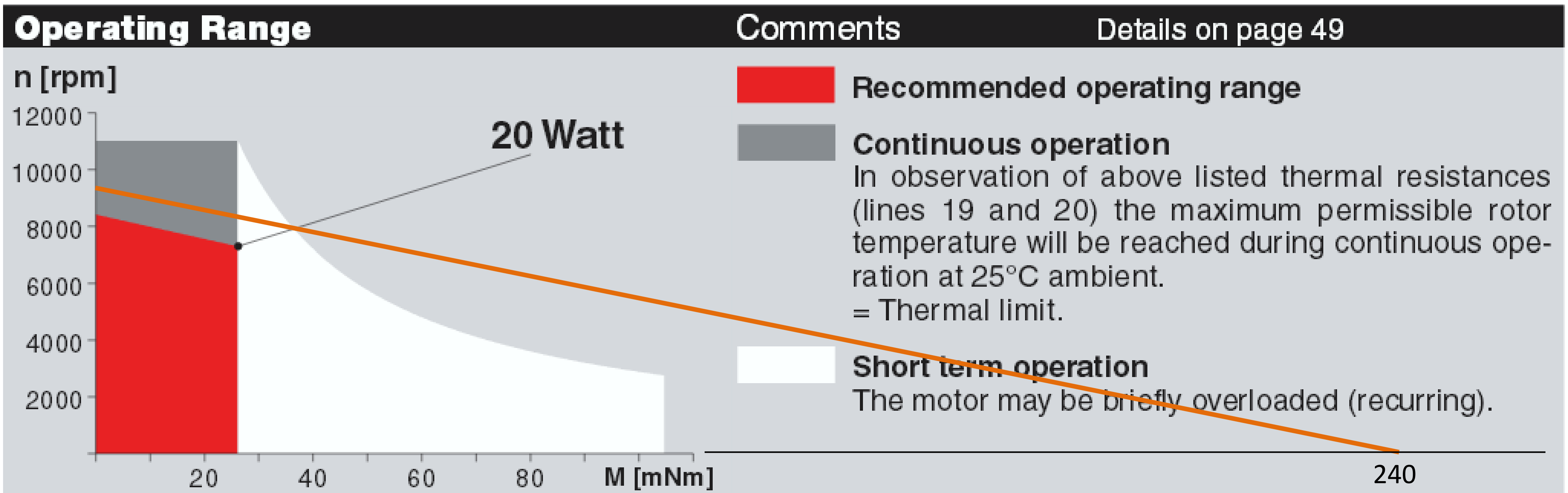
Note that the max. power output listed here is closer to our theoretical calculation

DC MOTOR SPECIFICATIONS

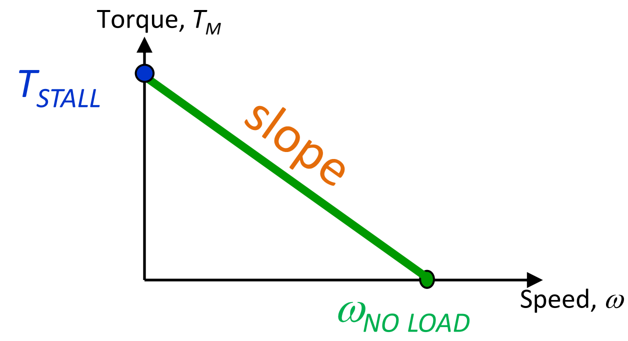
$$T_M = K_T \cdot i_a$$

This manufacturer is conservative in its recommendations…



This manufacturer recommends keeping the torque at about 1/8th of stall torque for continuous operation! A more common rule of thumb is limiting continuous torque from 1/3 to 1/2 the stall torque. The higher the continuous torque, the closer you need to watch the motor temperature!

DC MOTORS



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15	Speed constant	rpm / V				412					
16	Mechanical time constant	ms				5					
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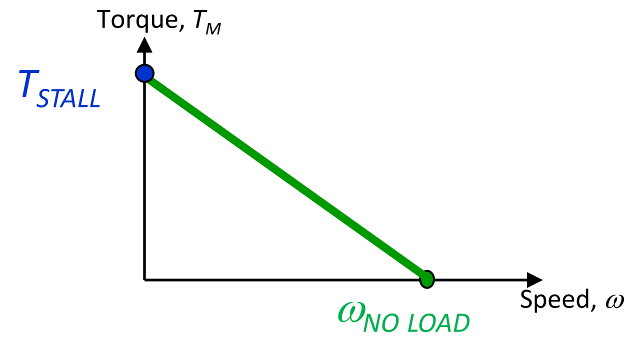
19	Thermal resistance housing-ambient	K / W				14					
20	Thermal resistance rotor-housing	K / W				3.1					
21	Thermal time constant winding	s				12					

DC MOTORS

How can the motor speed be greater than no load speed?



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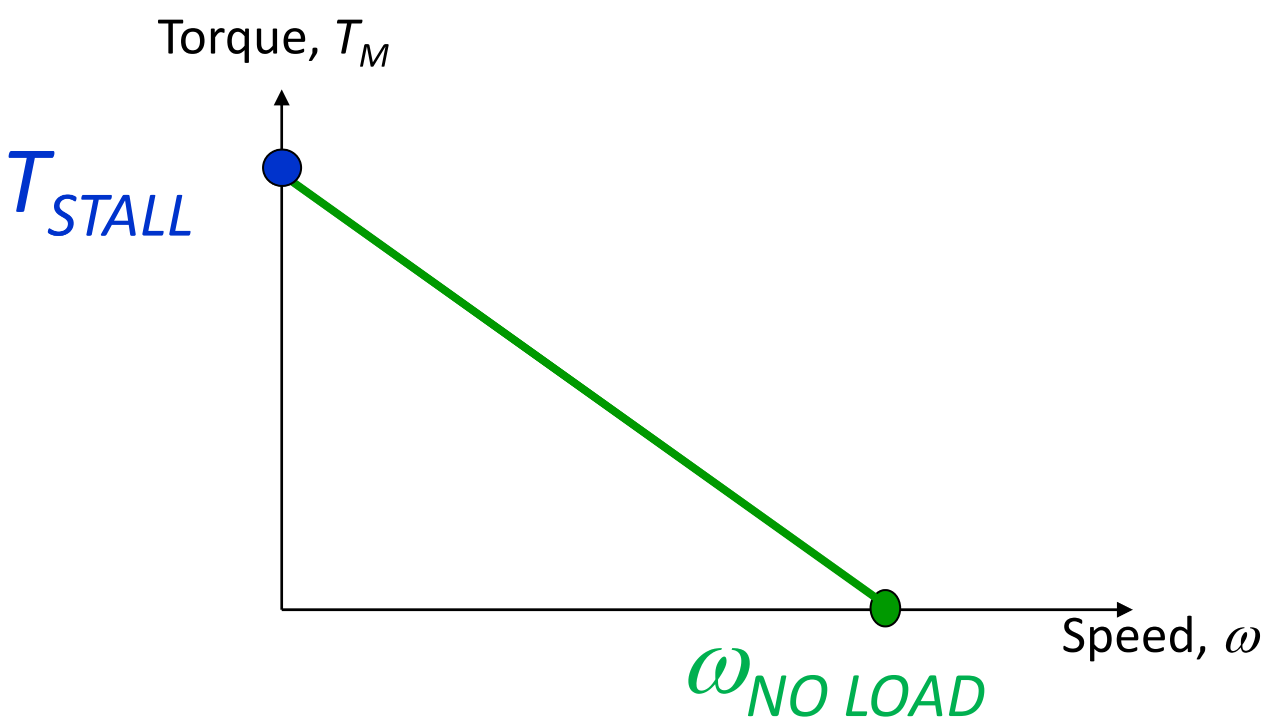
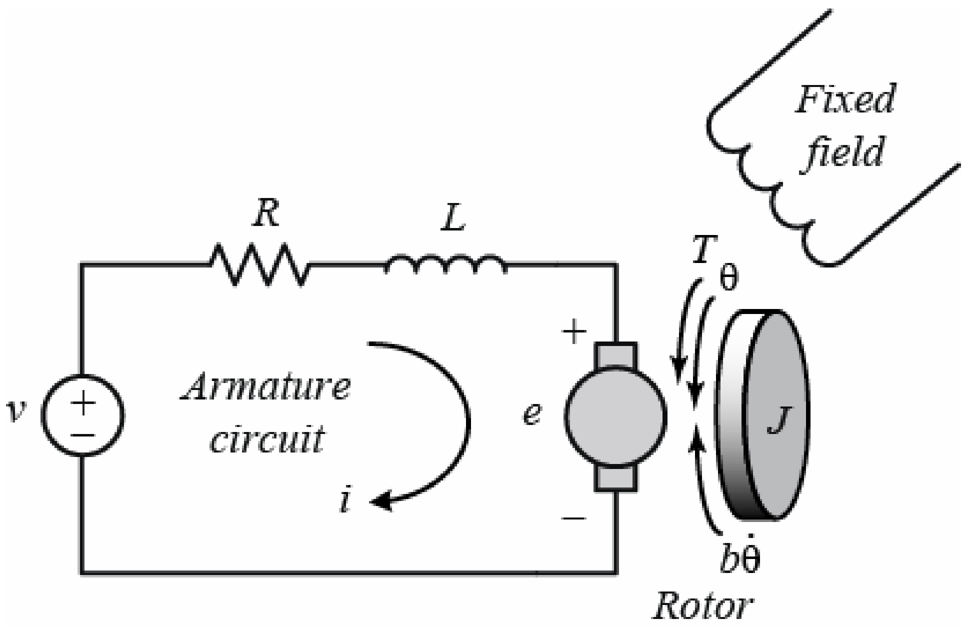
WHY DOES THE TORQUE CURVE HAVE A DOWNWARD SLOPE?



RECALL: TWO FUNDAMENTAL PRINCIPLES FOR DC MOTORS

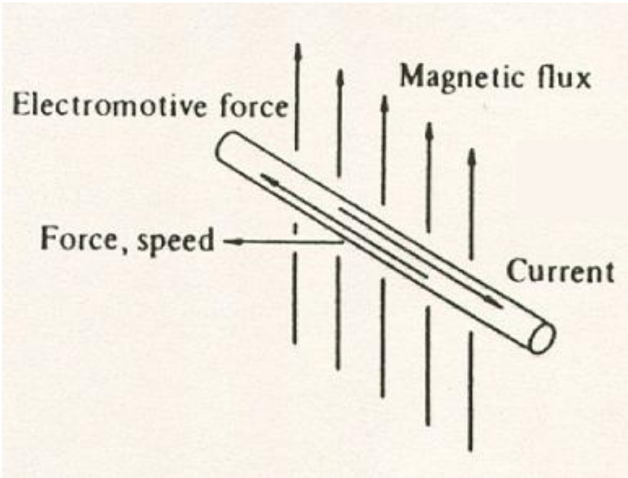


- **Torque Production**: We've talked about this already…
- **Back EMF**: Now let's cover the causes and effects of ***counter-electromotive force*** (EMF), also known as back EMF.

BACK-EMF GENERATION

- Electromotive force (EMF) is generated in a conductor moving in a magnetic field:

$$de_{EMF} = \left(\vec{v} \times \vec{B}\right) \cdot d\vec{L}$$

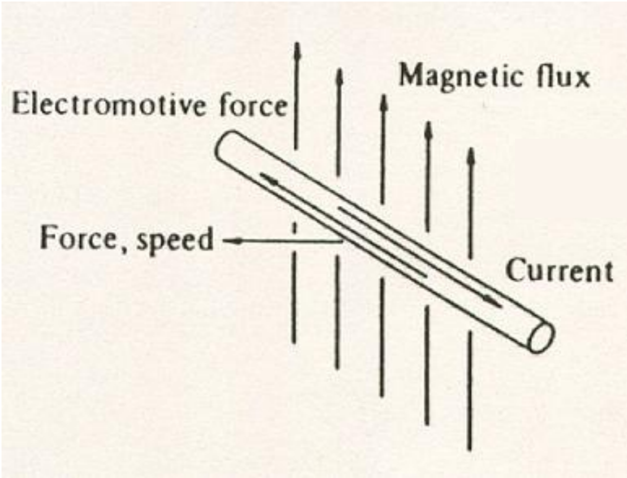


Despite the name, EMF is a ***voltage***, not a mechanical force!

Back-EMF ***opposes*** the voltage applied to drive a DC motor.

BACK-EMF GENERATION

- Electromotive force (EMF) is generated in a conductor moving in a magnetic field: $de_{EMF} = (\vec{v} \times \vec{\mathcal{B}}) \cdot d\vec{L}$

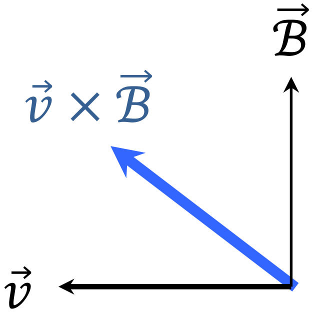


- Integrate over the entire length L:

$$e_{EMF} = v \cdot \mathcal{B} \cdot L$$

- Since the N armature coils are in series, the total EMF is:

$$V_{EMF} = 2N\underbrace{(R\omega)}_{v}BL = (2 \cdot N \cdot R \cdot \mathcal{B} \cdot L) \cdot \omega$$



- Define the Back-EMF Constant K_{EMF}:

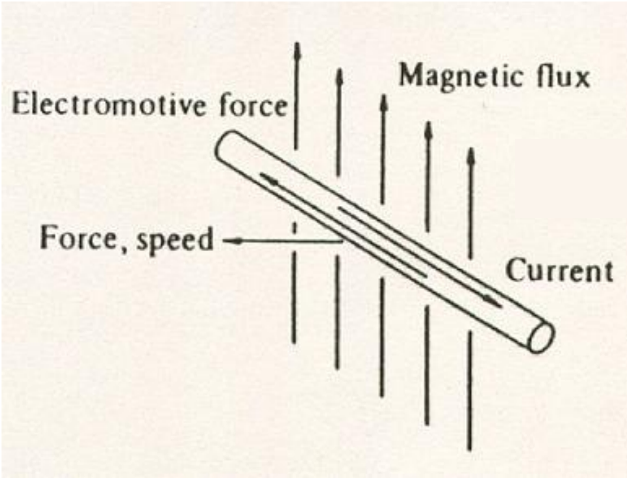
$$K_{EMF} = 2 \cdot N \cdot R \cdot \mathcal{B} \cdot L \quad \text{[V/(rad/sec)]}$$

BACK-EMF GENERATION

- Back-EMF Constant K_{EMF}:

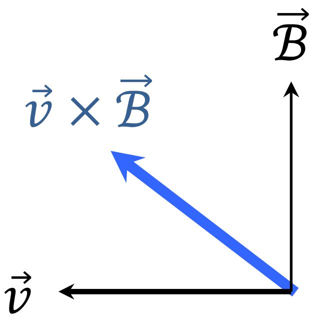
$$K_{EMF} = 2 \cdot N \cdot R \cdot \mathcal{B} \cdot L \quad [\text{V/(rad/sec)}]$$

Note: *$K_T = K_{EMF}$ only if SI units are used* !



- Back-EMF generated due to the rotation of the motor armature opposes the applied voltage and is proportional to the angular speed w of the motor:

$$V_{EMF} = K_{EMF} \cdot \omega$$



DC MOTOR SPECIFICATIONS

This spec sheet gives the inverse of K_{EMF}

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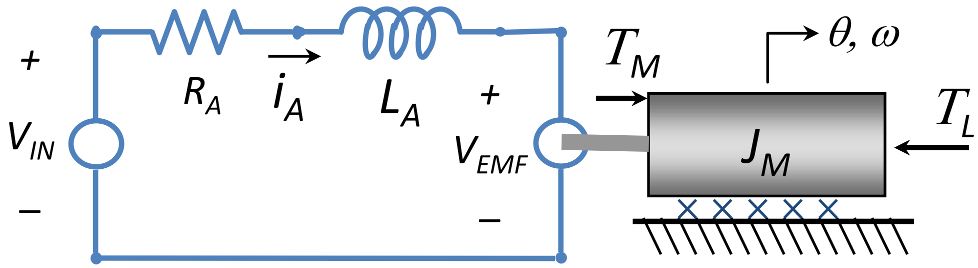
DC MOTORS OPERATE USING TWO FUNDAMENTAL PRINCIPLES

- Torque Generation

$$T_M = K_T \cdot i_A$$

- Back-Electromagnetic Force (EMF)

$$V_{EMF} = K_{EMF} \cdot \omega_M$$



In SI units, $K_T = K_{EMF}$

DC MOTOR SPECIFICATIONS

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DC MOTOR OPERATING CHARACTERISTICS

From a ***control*** view of a DC motor

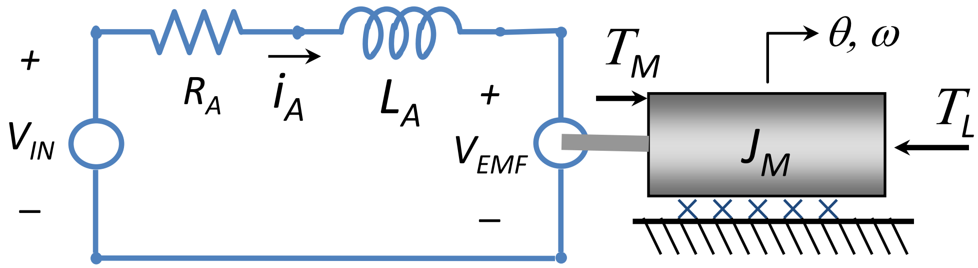
- We treat the "motor" as a box that is lossless and stores no energy. In reality, power losses exist due to internal resistance and friction.

PMDC MOTOR OPERATING CHARACTERISTICS

- At steady state, power flow on the mechanical and electrical sides instantaneously match (why?)

$$P = \underbrace{V_{IN} \cdot i}_{\text{Electrical power}} = \underbrace{T \cdot \omega}_{\text{Mechanical power}}$$

$$P = K_{EMF} \cdot \omega \cdot \frac{T}{K_T} = T \cdot \omega$$

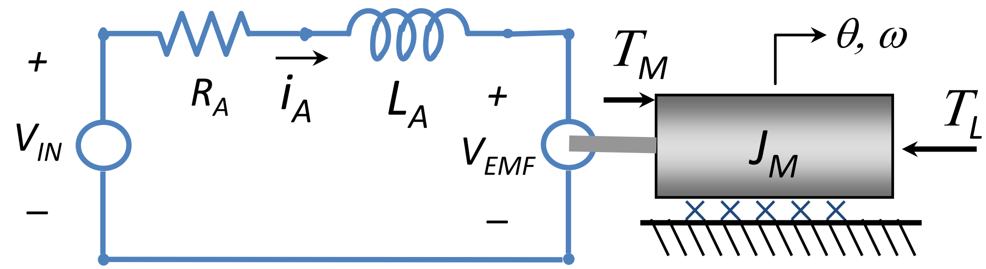


During constant speed operation, the input voltage is equal to the back-EMF generated by the motor, since $T = K_T \cdot i$ and $K_{EMF} = K_T$. Hence, by maintaining a constant supply voltage of $V_{IN} = K_{EMF} \cdot \omega$, we achieve a constant output speed

PMDC MOTOR OPERATING CHARACTERISTICS

Equivalent circuit:

$$V_{IN} = i_A \cdot R_A + V_{EMF} + \cancel{L_A \cdot \frac{d}{dt} i_A}$$



At steady-state:

$$V_{IN} = i_A \cdot R_A + V_{EMF} = \frac{T_M}{K_T} \cdot R_A + K_{EMF} \cdot \omega$$

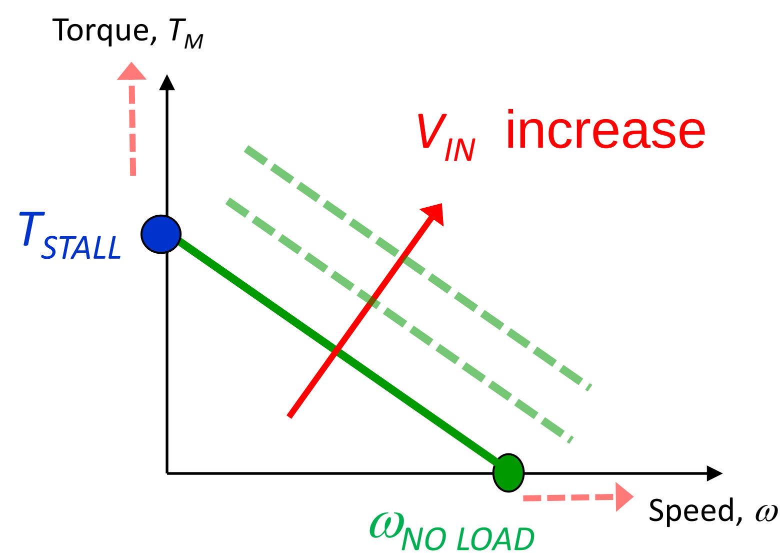
$$\Rightarrow T_M = \frac{K_T}{R_A}(V_{IN} - K_{EMF}\,\omega)$$

- Stall Torque (ω = 0):

$$T_{STALL} = \frac{K_T}{R_A} \cdot V_{IN}$$

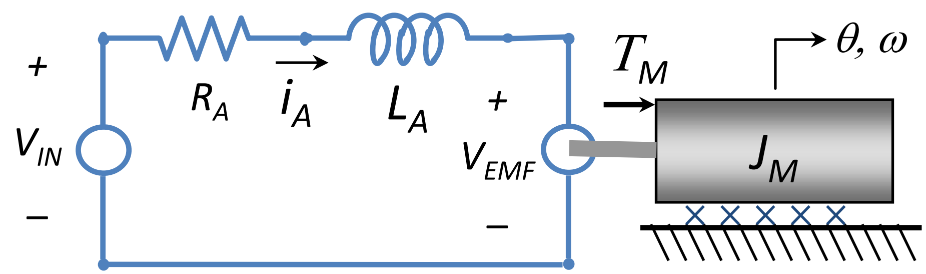
- No-Load Speed (T_M = 0):

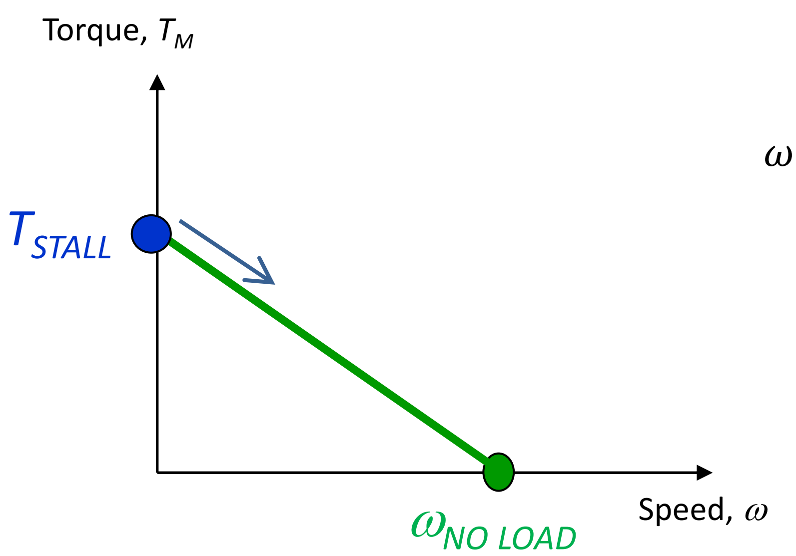
$$\omega_{NO\ LOAD} = \frac{V_{IN}}{K_{EMF}}$$

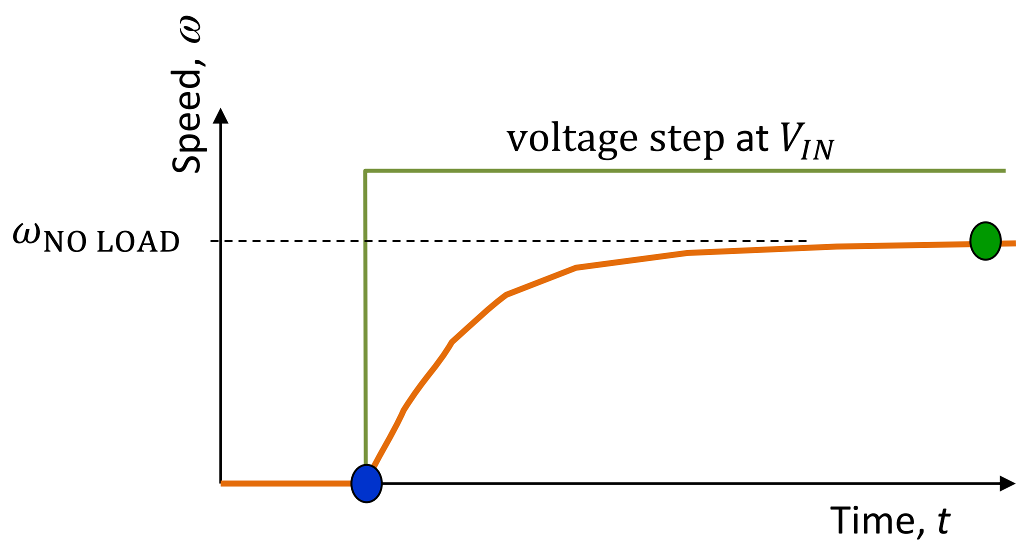


PMDC MOTOR OPERATING CHARACTERISTICS (NO LOAD)

- For a step voltage input, rapid acceleration occurs as motor starts from a standstill. As more and more back EMF is generated, the motor torque decreases, and acceleration slows, with the speed eventually settling at $\omega_{\text{NO LOAD}}$.

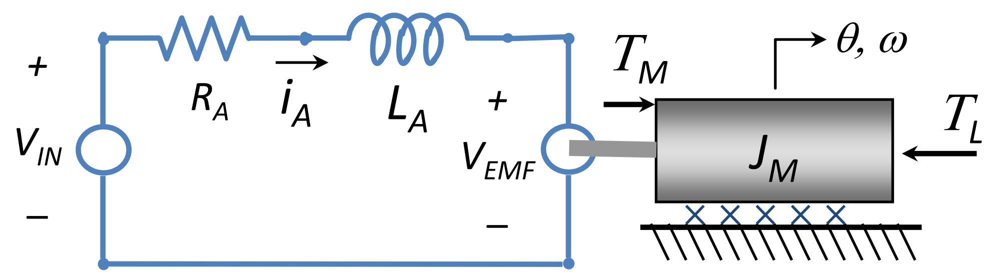




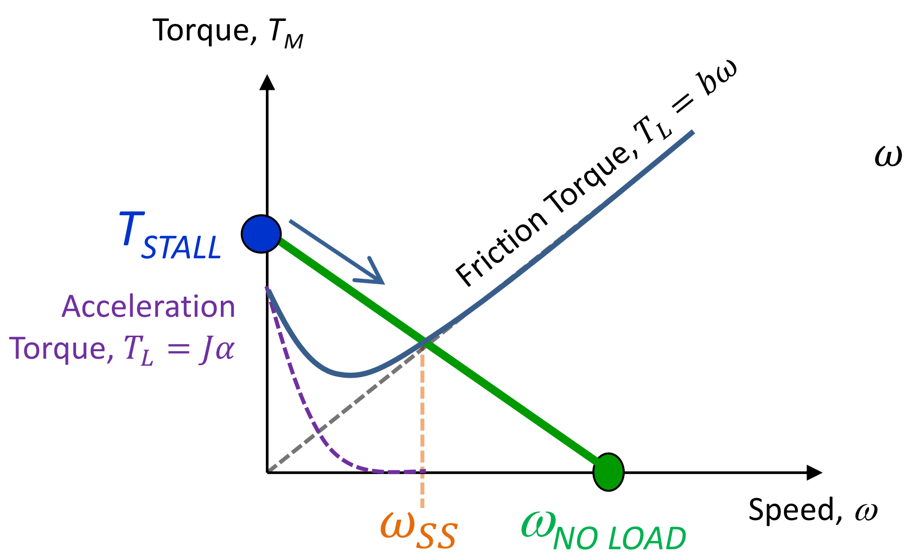


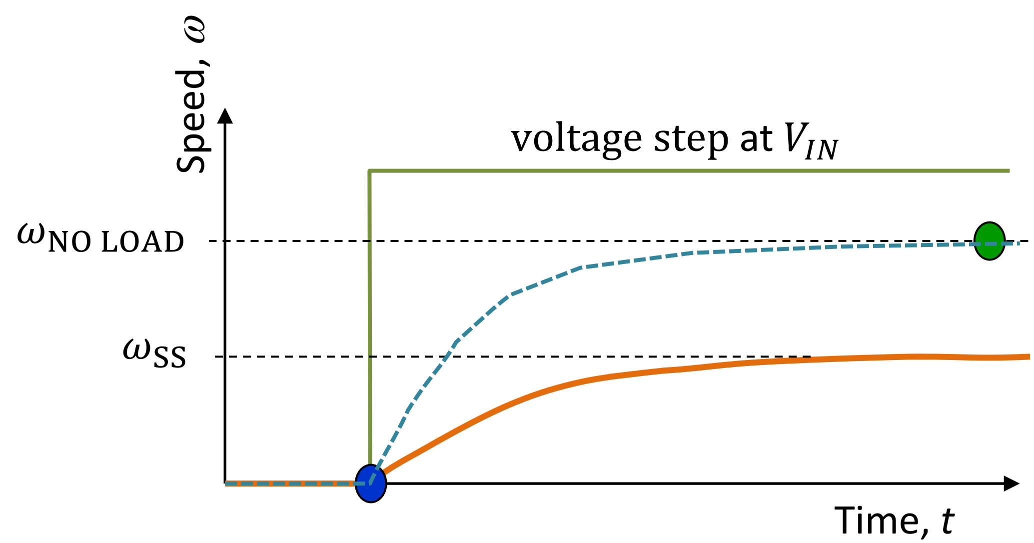
PMDC MOTOR OPERATING CHARACTERISTICS (WITH LOAD)

Q: Does the load on the mechanical side affect the steady-state speed?



$$T_L = J\alpha + b\omega$$





DC MOTOR SPECIFICATIONS

The mechanical time constant tells us the time it takes an unloaded motor to reach 63% of its no-load speed under a constant voltage, when starting from rest

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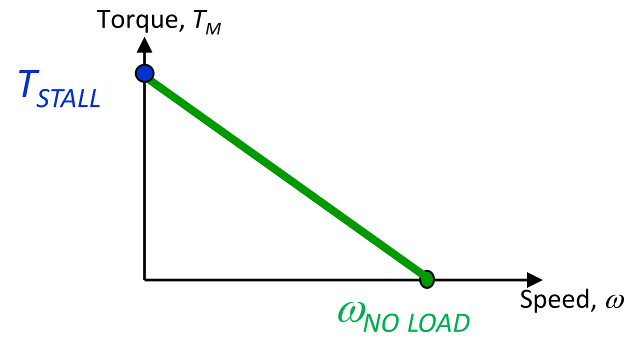
DC MOTOR SPECIFICATIONS



Why doesn't the no load current go to zero?

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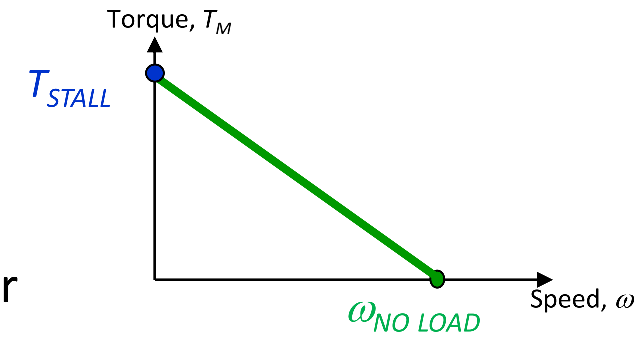
DC MOTOR SPECIFICATIONS



Maximum efficiency in converting electrical power to mechanical power usually occurs at high speeds and low torques

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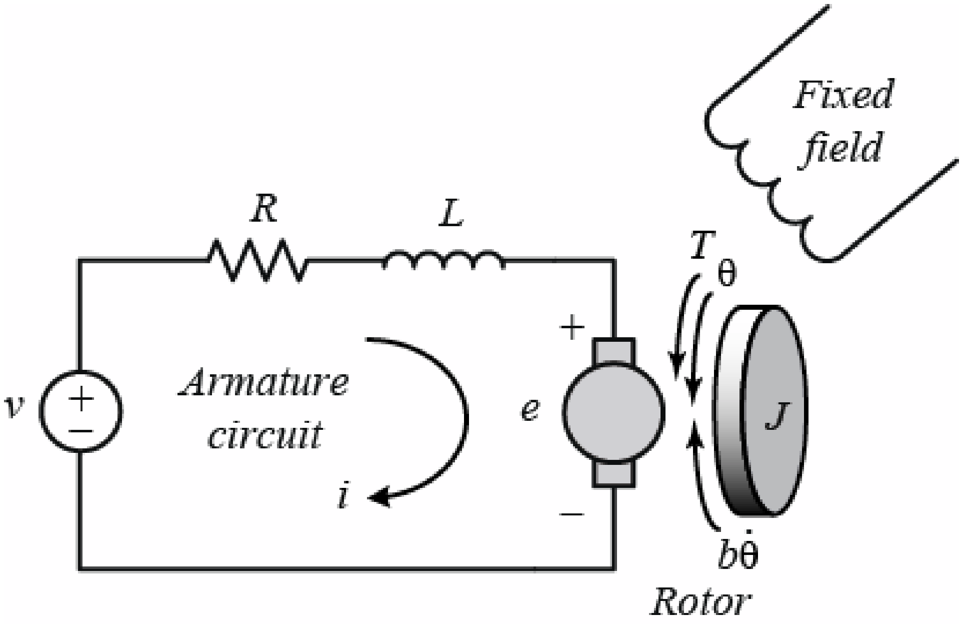
WE CAN CONTROL A DC MOTOR IN TWO DIFFERENT METHODS



$$V_{EMF} = K_{EMF} \cdot \omega$$

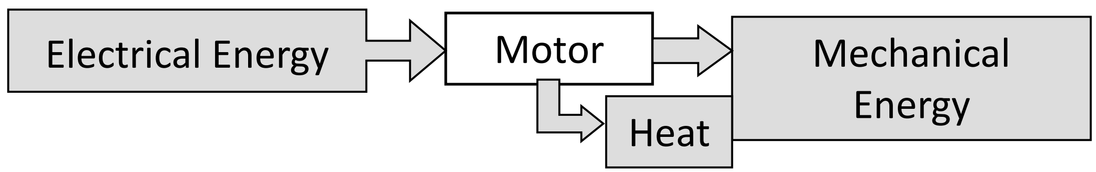
$$T_M = K_T \cdot i_A$$

- **Voltage (velocity) mode**: control voltage across winding
- **Current (torque) mode**: control current through winding

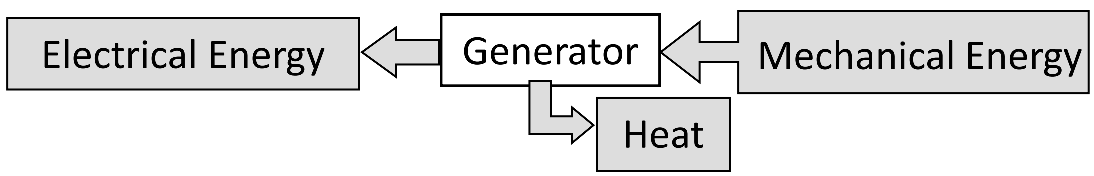
DC MOTOR OPERATION MODES

Generator/Tachometer

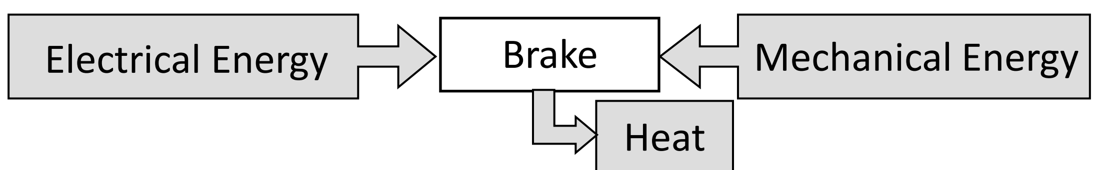
- The operating equations do not depend on direction of power flow:
  - Motor – Electrical power in → mechanical power out.



  - Generator – Mechanical power in → electrical power out.
    - When operated for its output power, it is called a generator.



    - Generator operating mode can be viewed as adding a load. Some application it is called a dynamometer or dynamic breaking.



- Can also be operated as a speed sensor:
  - Back-EMF is proportional to the speed of the rotor.
  - Measure open-circuit voltage across winding – *tachometer*.

FACTORS TO CONSIDER WHEN SELECTING A MOTOR

We often want more torque, but we can't increase torque without increasing current. However, ***too much current will destroy the motor windings***! Thus, we must take a look at the following constraints when selecting a DC motor:

- Torque limits
- Current limits
- Rotational speed limits

FACTORS TO CONSIDER WHEN SELECTING A MOTOR

Even if we don't burn out the windings, we can overheat the motor:

- Heat is primary performance limitation for DC motors
- Sources:
  - Electrical losses in windings
  - Eddy current
  - Hysteresis
  - Friction
  - Brush contact resistance
- Transient temperature limit is very different from steady-state limits (what is on the specifications)

FACTORS TO CONSIDER WHEN SELECTING A MOTOR

If you need more torque, however, do not fear…

As we will see shortly, you can trade speed for torque using a gearbox!

COMING UP…

System Interfacing

- Alternate means for magnetic field generation
- Brushless DC motors
- Gearing and gearboxes
- Stepper Motors