19-DC Machine Principles

ECEGR 3500

Text: Chapter 12.7

Electrical Energy Systems

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Basic Principles of Electric Machines

- Recall that a relative motion between a conductor and constant magnetic field induces an emf
  - A coil can rotate in a fixed magnetic field
  - A fixed coil in a rotating (varying) magnetic field

$$\boldsymbol{F} = \int_c i d\ell \times \boldsymbol{B}$$

- DC machines: stationary magnetic field, rotating coil
- AC machine: stationary coils, rotating magnetic field

Basic Principles of Machines

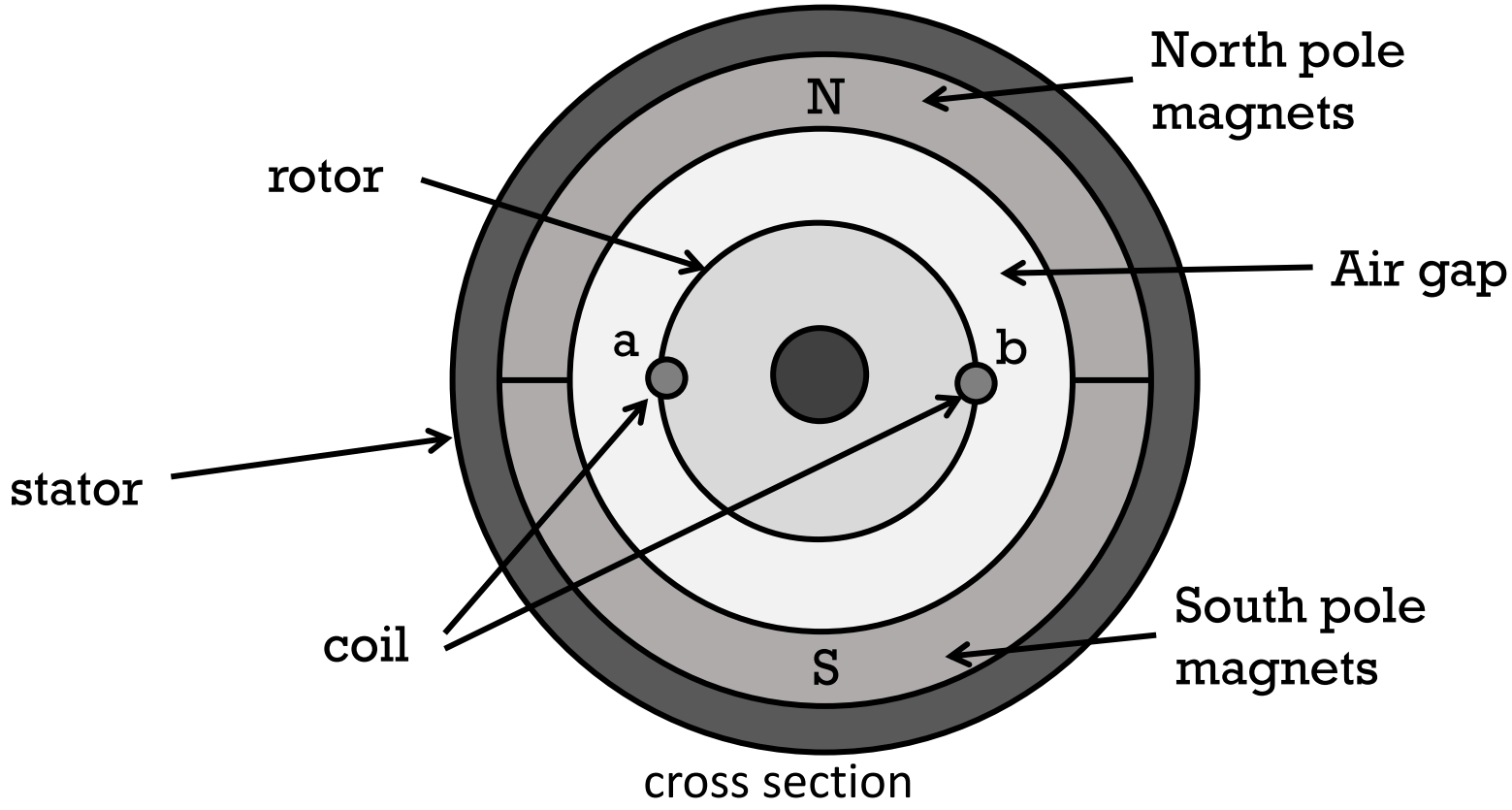
- Generically:
  - Rotating part is known as the *rotor* (also known as the *armature* in dc machines)
  - Stationary part is known as a *stator*
- Rotor and stator are made from highly permeable material
- A small air gap between stator and rotor allows the rotor to rotate
  - Air gap consumes most of the mmf (similar to large voltage drop)

Basic Principle of Machines

- How can a constant magnetic field be set up?
  - Permanent magnet (PM)
  - Electromagnet (also known as a wound machine)
  - Both have advantages and disadvantages
- For clarity, we will assume PM DC machines for now
- We will discuss AC machines later

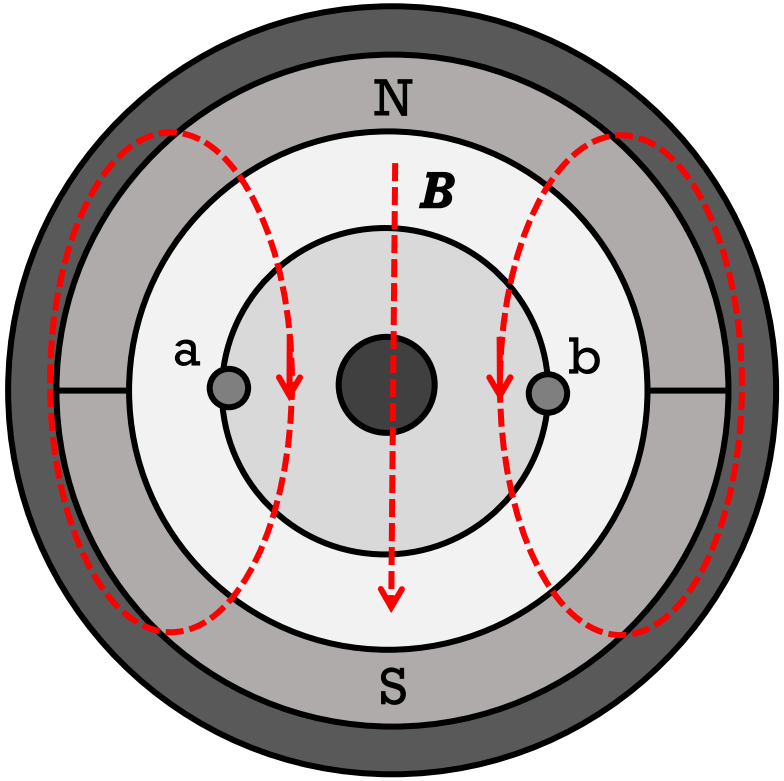
Generator Action

Consider an idealized cylindrical rotating machine with two poles (North and South)



Generator Action

- Ends of the coil are placed 180° apart
  - *full pitch*
- As the rotor rotates, one end of the coil enters N, just as the other enters S
- Note the magnetic field approximation



Generator Action

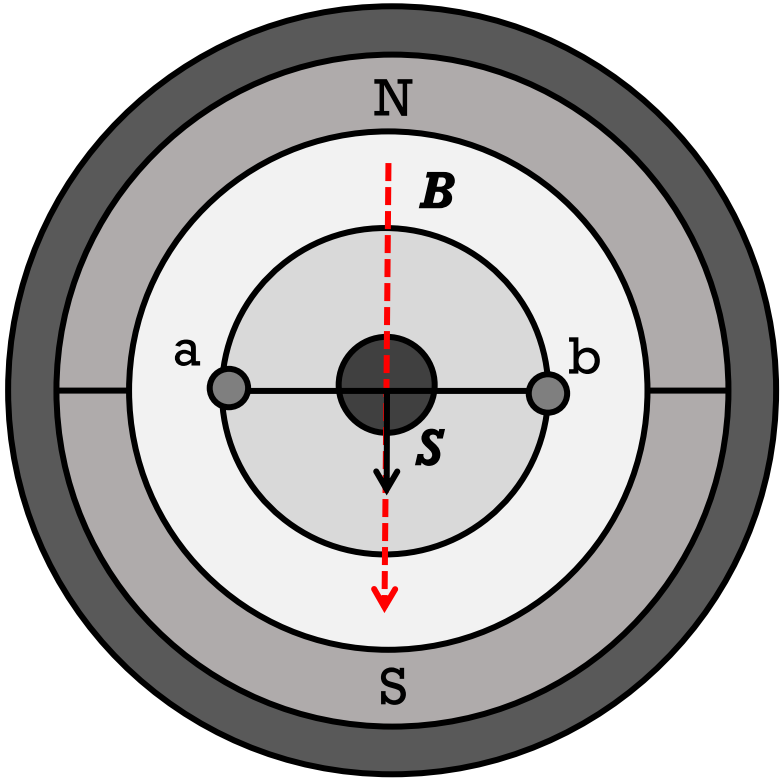
- Assume $\boldsymbol{B}$ and $d\boldsymbol{S}$ are normalized values so that

$$|\boldsymbol{B}||d\boldsymbol{S}| = 1.0$$

- If the coil is at rest, no emf is induced

$$e = -\int_s \frac{\partial \boldsymbol{B}}{\partial t} \cdot d\boldsymbol{s} = -N\frac{d\Phi}{dt}$$

N = 1 for single-turn coils

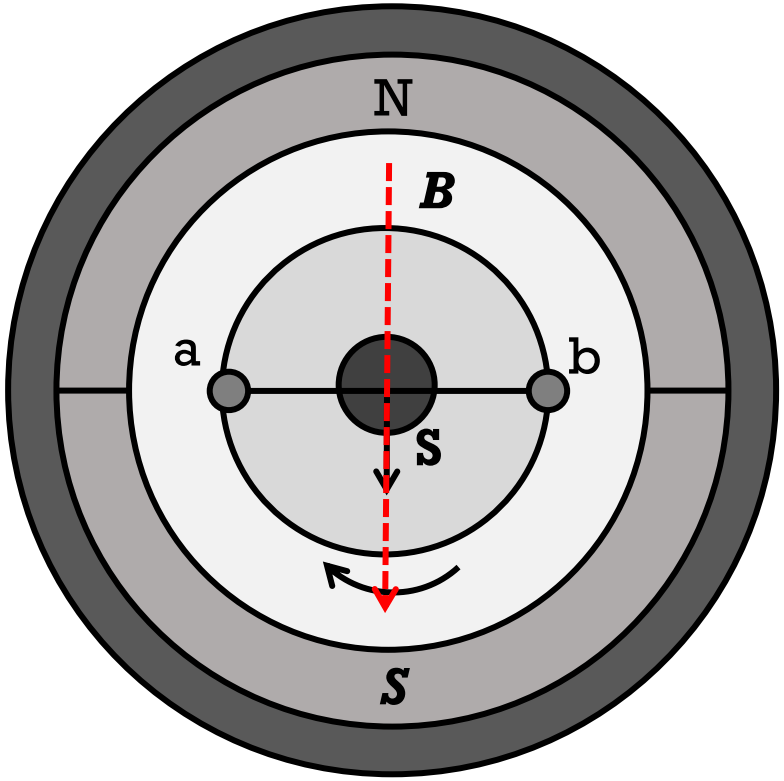


Generator Action

- θ_m: angle of rotation (angle between ***B*** and ***S***)

$$\mathbf{B} \bullet \mathbf{S} = |\mathbf{B}||\mathbf{S}| \cos\theta_m = 1.0$$

- Flux through the coil is maximum (***B*** and ***S*** are aligned)
- Following slides: rotor is rotated CW by an external torque

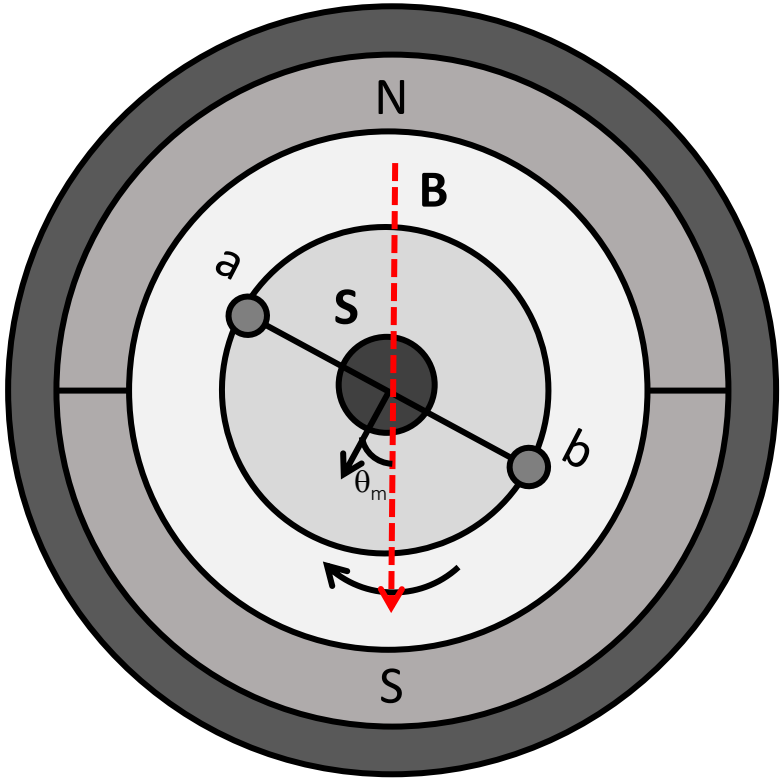


$\theta_m = 0^o$

Generator Action

- Now the coil has 30°
- Has the flux increased or decreased?
  - Decreased

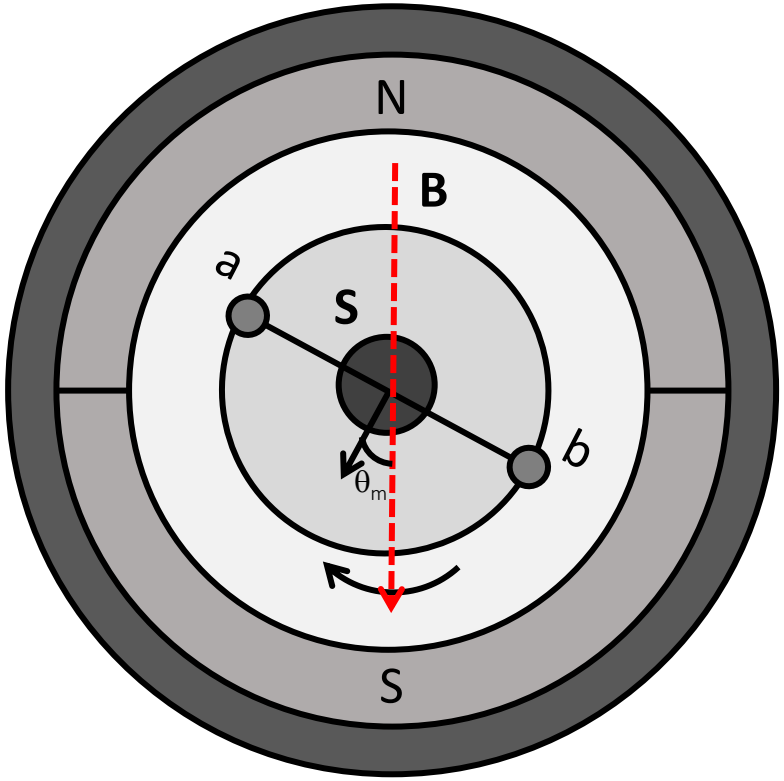
$$|\boldsymbol{B}||\boldsymbol{S}|\cos\theta_m = 0.866$$



$\theta_m = 30°$

Generator Action

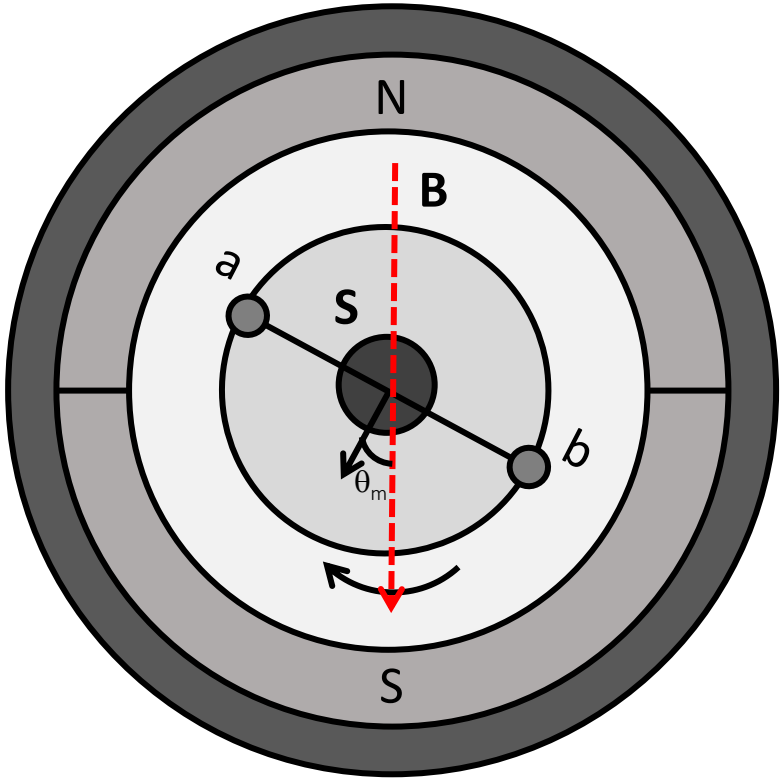
- If the ends of the coil are connected to a closed circuit, what direction does the current flow due to the induced emf?
- Is the current into a and out b, or into b and out a?



$\theta_m = 30^o$

Generator Action

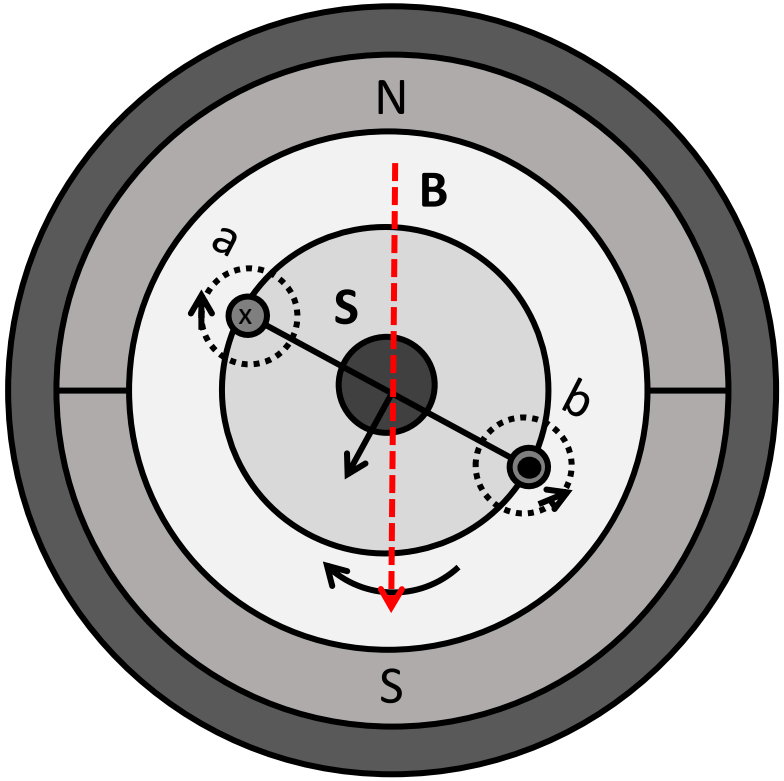
- Recall that the induced current flows in such a way that the flux it creates opposes the change in flux that caused it



$\theta_m = 30^o$

Generator Action

- If the induced current is going into a and out b, then the associated magnetic fields would be as shown
- Does this increase or decrease the flux through the coil?
  - Increases it, so it is the correct direction
  - The induced emf is therefore positive from a to b



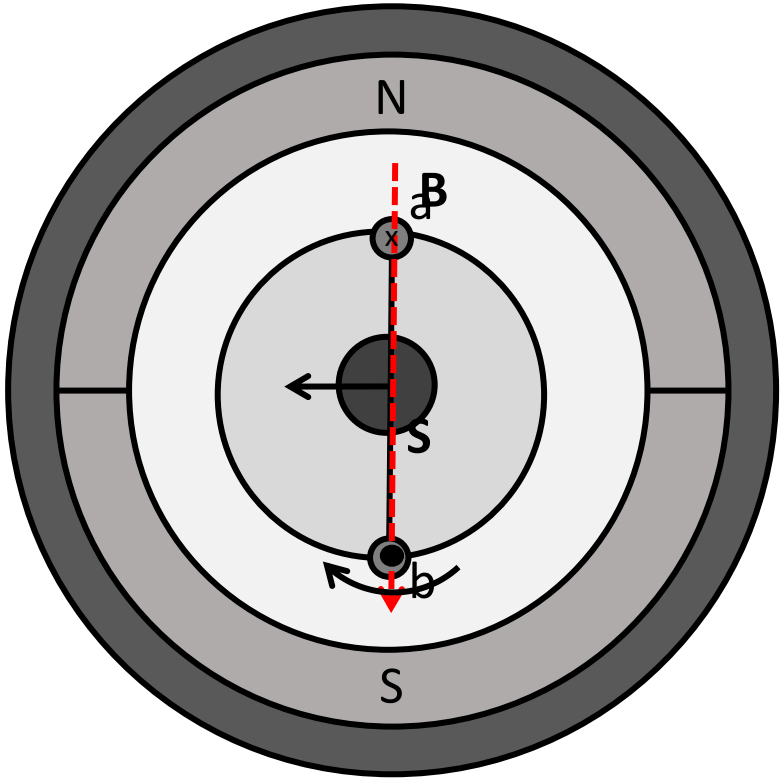
$\theta_m = 30^o$

Generator Action

- Flux is at a minimum

  $|\mathbf{B}||\mathbf{S}|\cos\theta_m = 0$

- $d\Phi/dt$ is large
  - Large voltage is induced
- Flux has still decreased, so current is still into a and out of b



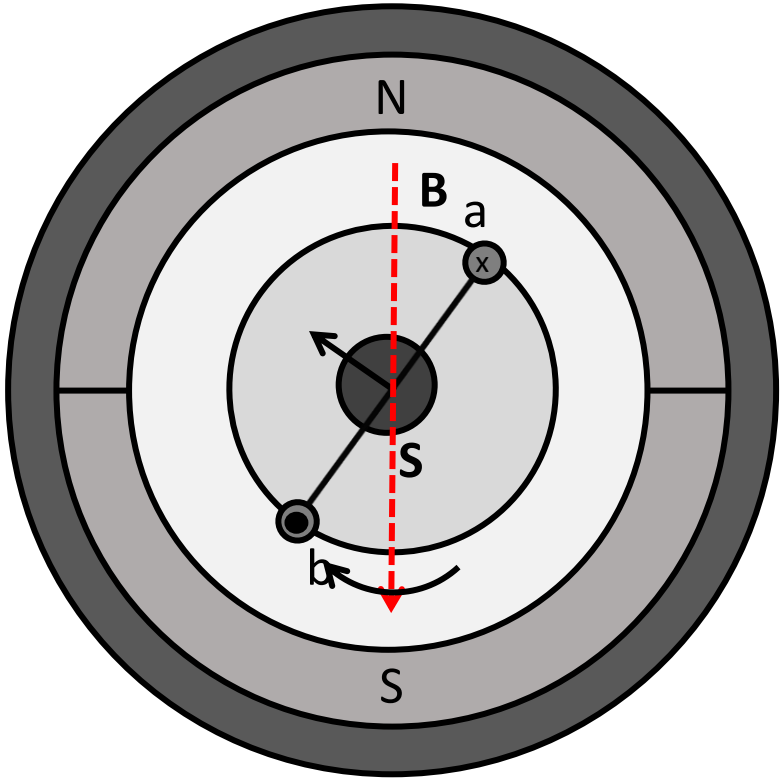
$\theta_m = 90^o$

Generator Action

- Flux is now in opposite direction through coil (negative)

$$|\mathbf{B}||\mathbf{S}|\cos\theta_m = -0.50$$

  - Induced current still flows into a and out of b



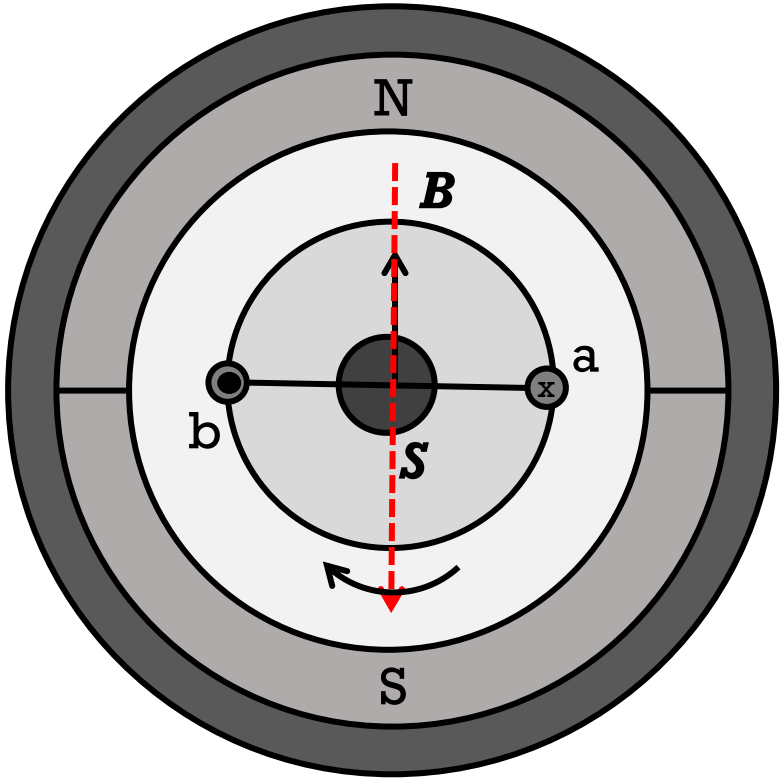
$\theta_m = 120^o$

Generator Action

- Flux is at its maximum negative value

$$|\boldsymbol{B}||\boldsymbol{S}|\cos\theta_m = -1$$

- $d\Phi/dt$ is small
  - small voltage is induced
- Flux has still decreased, so current is still into a and out of b



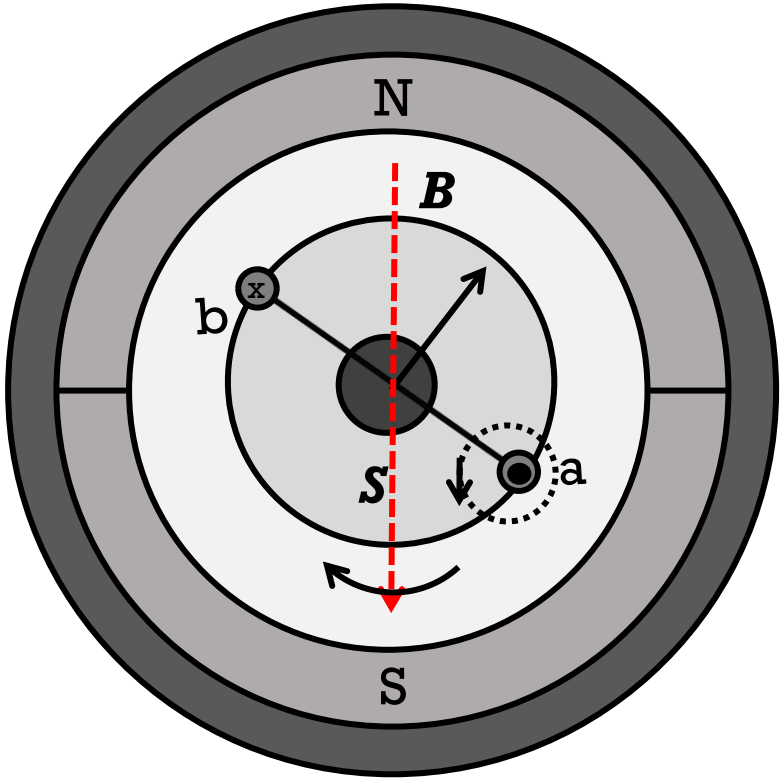
$\theta_m = 180^o$

Generator Action

- Flux starts to increase toward zero

  $|\boldsymbol{B}||\boldsymbol{S}|\cos\theta_m = -0.766$

- Induced current should act to decrease the flux
  - What direction is the current?
  - Into b and out of a
  - Polarity of voltage reverses
- Induced current stays in this direction until a full rotation is complete



$\theta_m = 220^o$

Generator Action

- Observations
  - Induced voltage lags flux by 90°
  - Induced voltage varies as a sinusoid
  - One full mechanical rotation equals one full electrical rotation (for 2-pole machines)
  - Alternating current is produced

Generator Action

- Analytically, the flux linking the coil is

$$\Phi = \Phi_P \cos\theta$$

  - Φ : flux linking the coil (Wb)
  - Φ_p: flux per pole (Wb)
  - θ: angular position of the coil (degrees electrical)

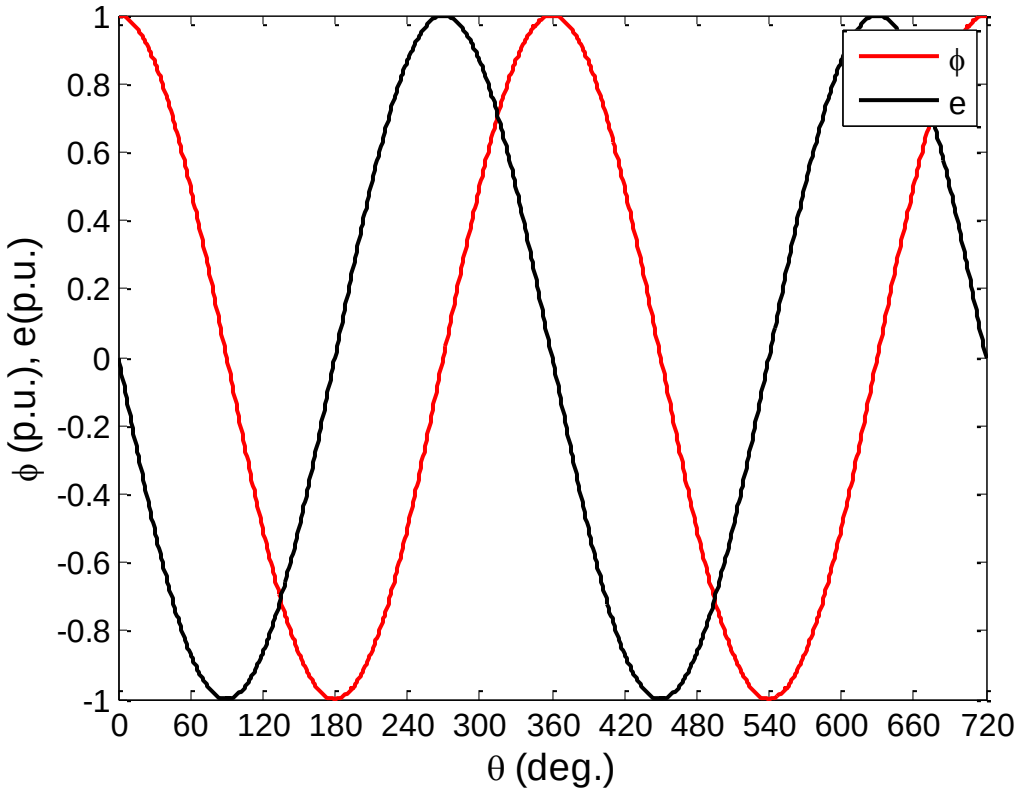
- The induced emf is:

Electrical and mechanical degrees are the same in 2-pole machines

$$\mathbf{e} = -\frac{d\Phi}{dt} = \Phi_P \sin\theta \frac{d\theta}{dt} = \Phi_P \omega \sin\theta$$

- Note that $\frac{d\theta}{dt} = \omega$ is the angular frequency of the coil

Generator Action



Exercise

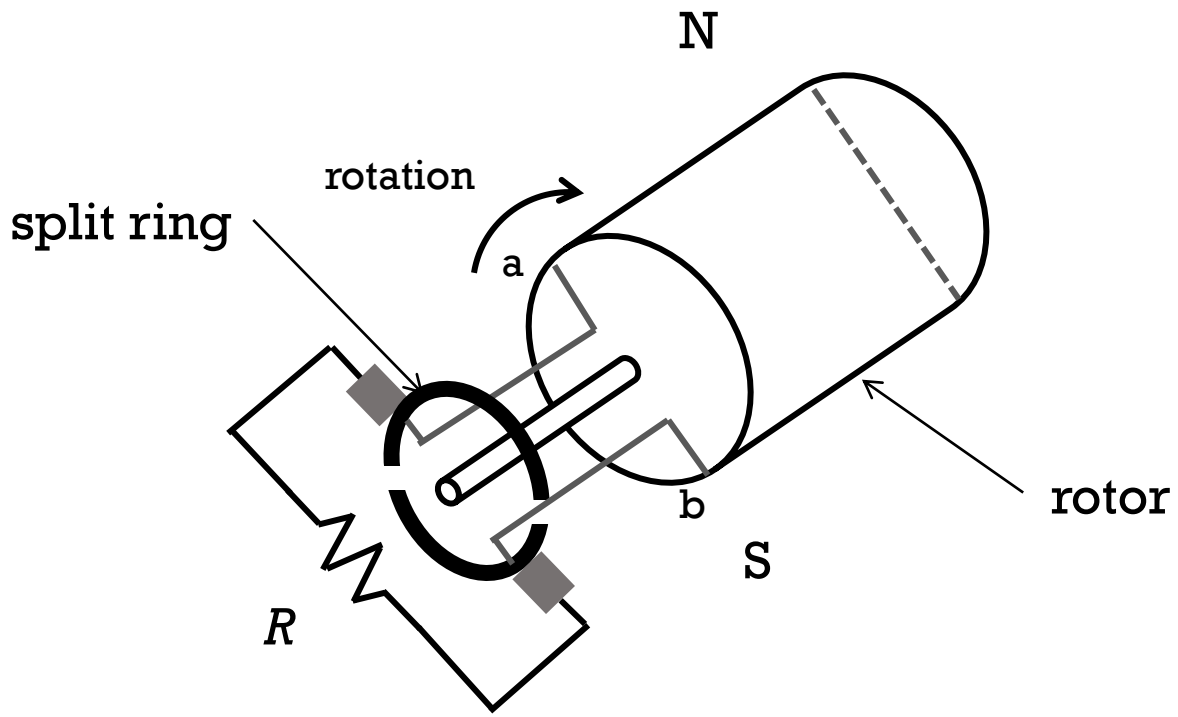
- Which of the following increases the induced voltage of the generator?
  - Decreasing the angular velocity
  - Increasing the flux per pole

Exercise

- Which of the following increases the induced voltage of the generator?
  - Decreasing the angular velocity
  - Increasing the flux per pole
    - Also increasing the angular velocity

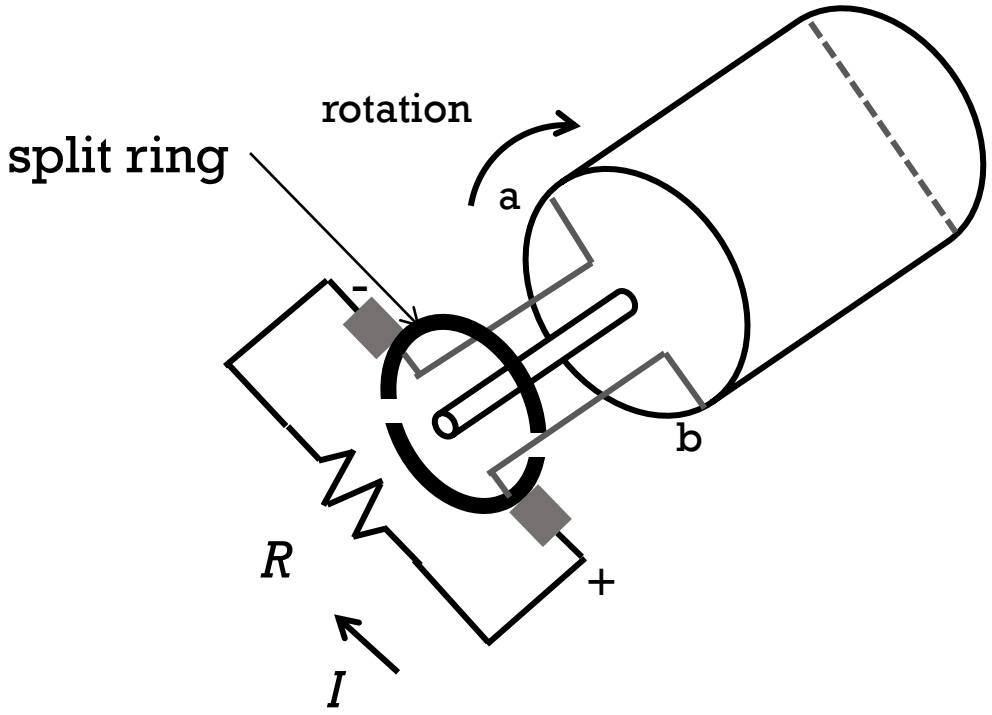
DC Machine

Connecting a rotor to a stationary circuit is problematic



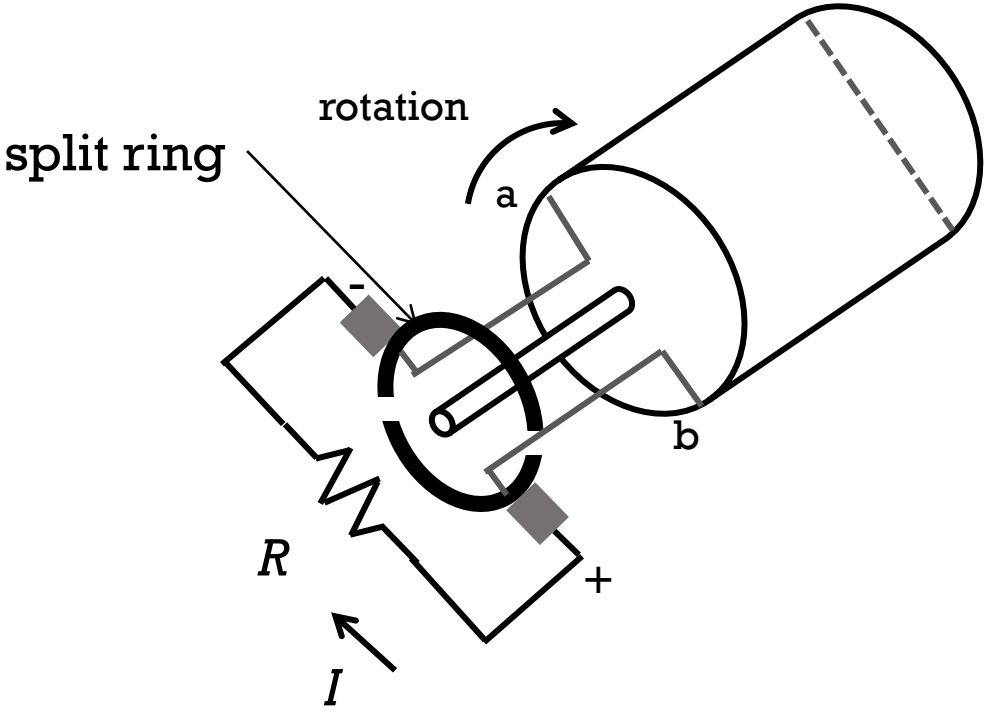
DC Machine

- Coil ends a and b are attached to either half of the split ring
- Stationary brushes are used to connect the split ring to the load R
- Current flows in one direction, but it is not constant



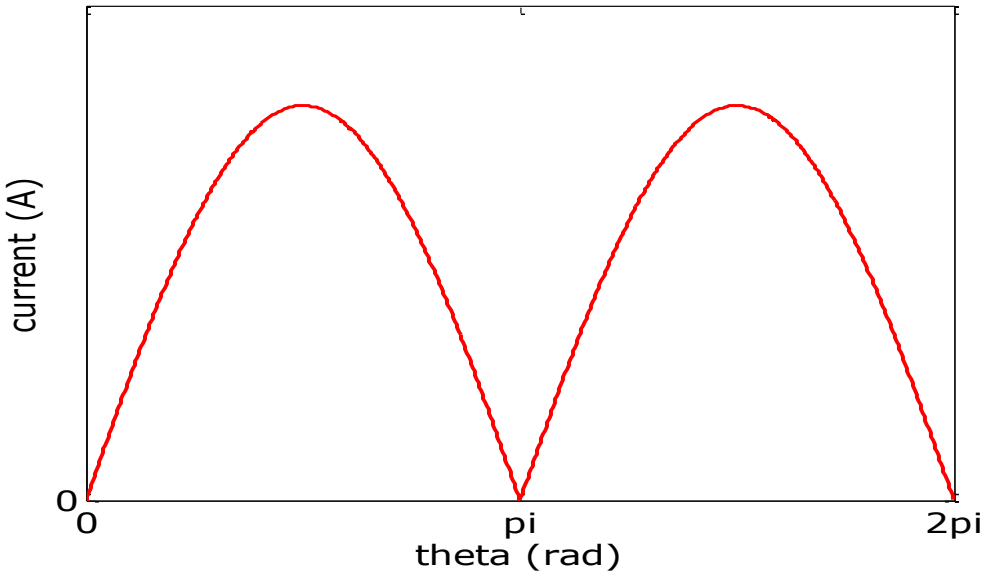
Exercise

What does the current waveform through the load R look like?



Exercise

- What does the current waveform through the load R look like?
- It is not a constant, but it is unidirectional



Force on a Conductor

- Recall that a current-carrying conductor in a magnetic field experiences a force in accordance with the Lorentz Force Equation:

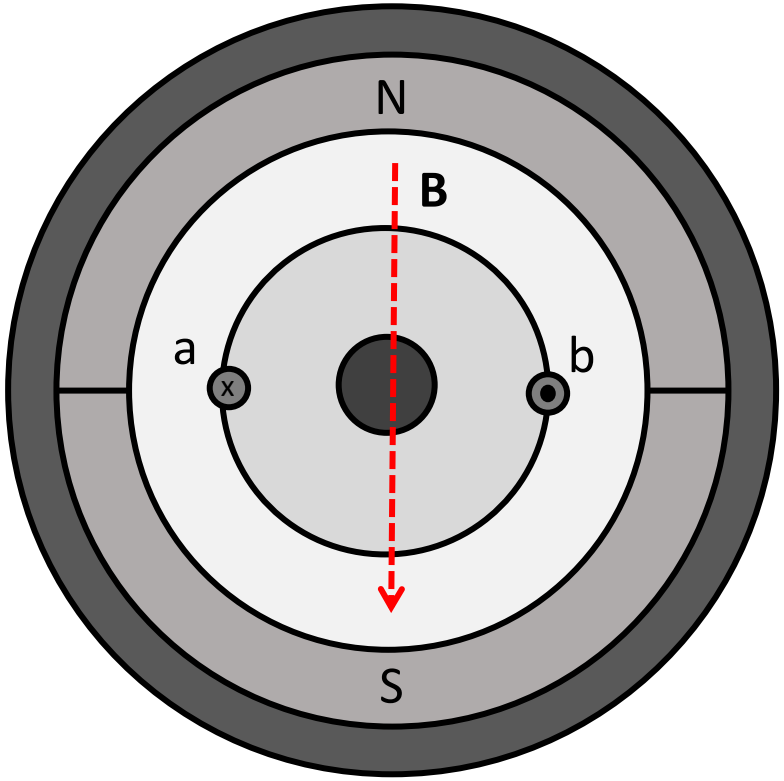
$$\mathbf{F} = \int_c \mathrm{I} d\boldsymbol{\ell} \times \mathbf{B}$$

$$\mathbf{F} = \mathrm{i}\boldsymbol{L} \times \mathbf{B}$$

- We will use this to understand how motors work

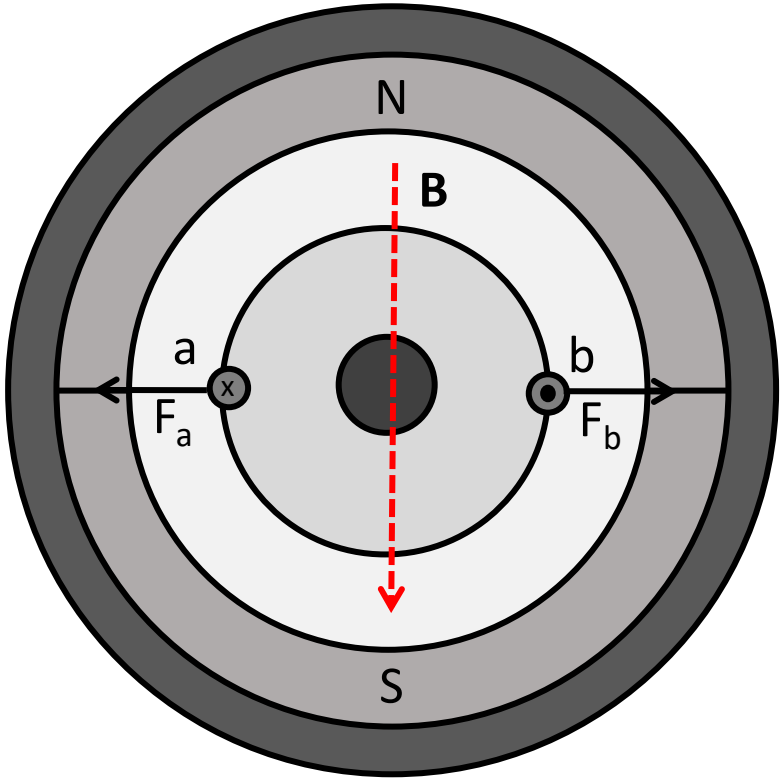
Exercise

- Consider a 2-pole machine
- Assume that coil ends a and b are connected to a constant voltage source with current into coil end a and out b
- What are the directions of the force on the conductor a and b?



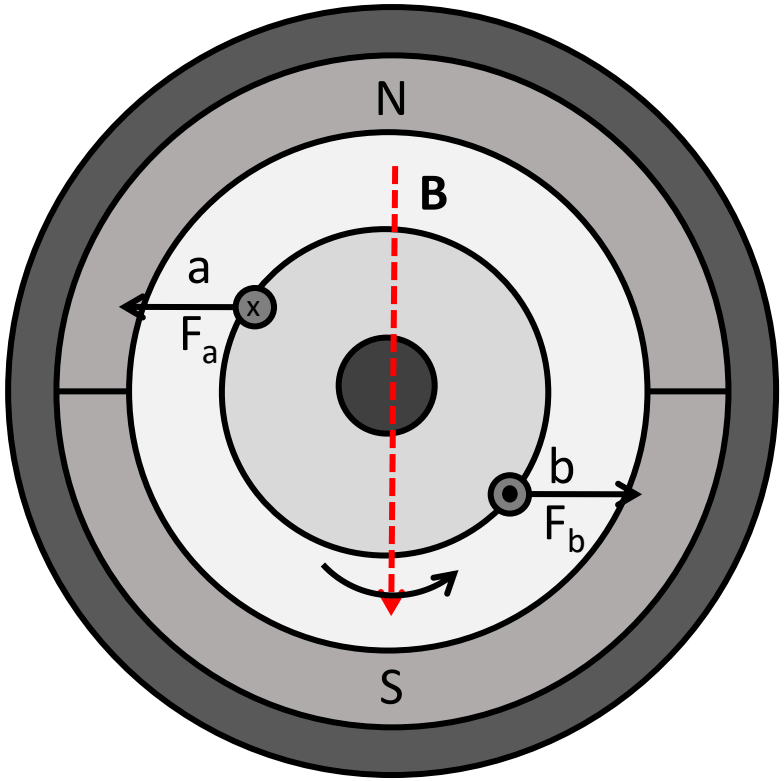
Exercise

- No net force or torque in this position
- What about other positions?



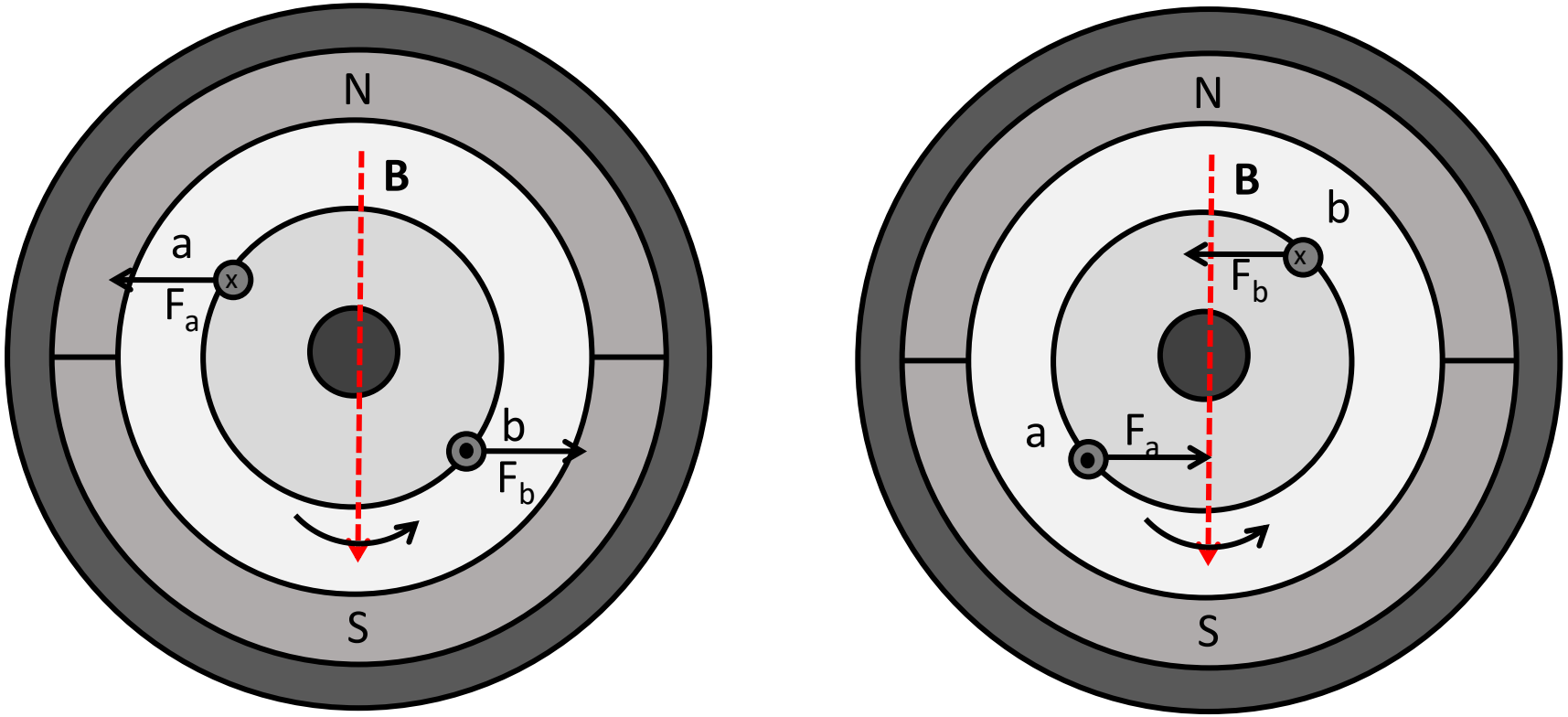
Motor Action

- Torque causes shaft to rotate in CCW direction
- If current polarity is reversed, rotation is in CW direction



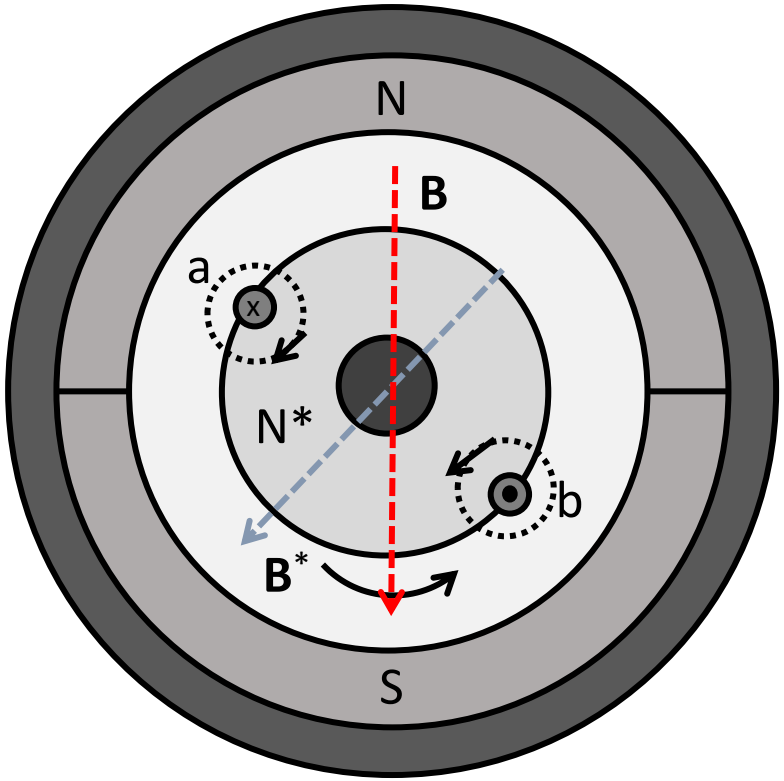
Motor Action

- Polarity must be reversed every half cycle to provide uni-directional rotation



Motor Action

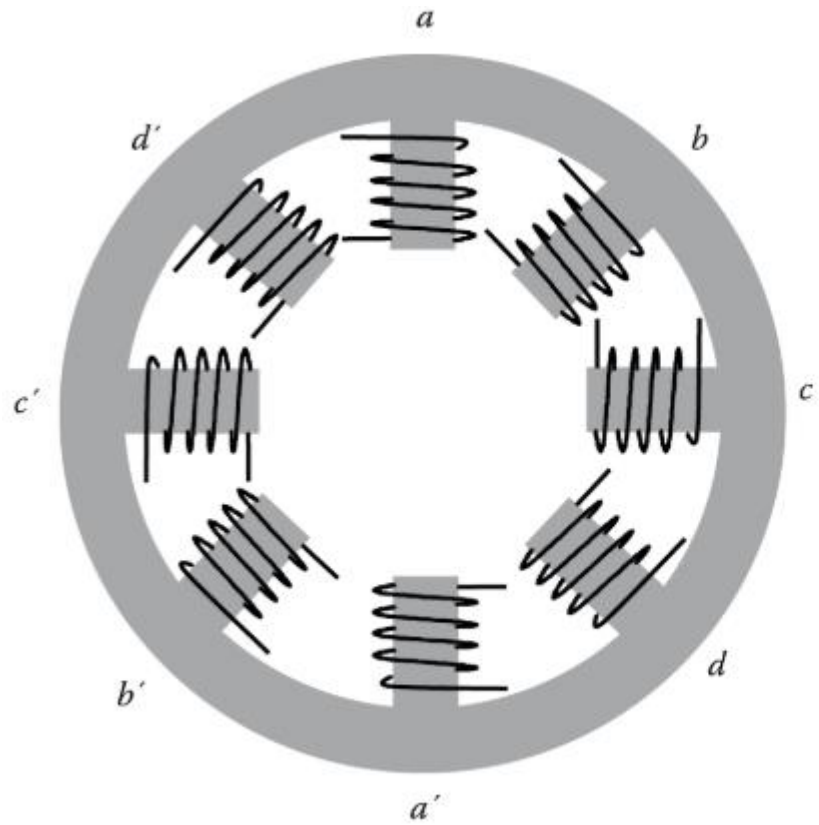
- We can also find rotation direction by thinking of the coil as an electromagnet
- Since flux leaves the North of a magnet, the direction of the electromagnet's North is N*
- This will try to align with the South of the stator
- Hence, counterclockwise rotation

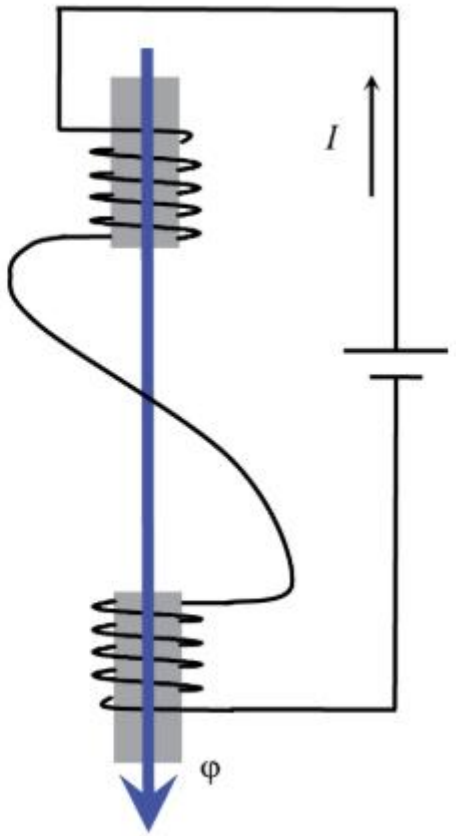


Stepper Motors (Read Chapter 12.8)

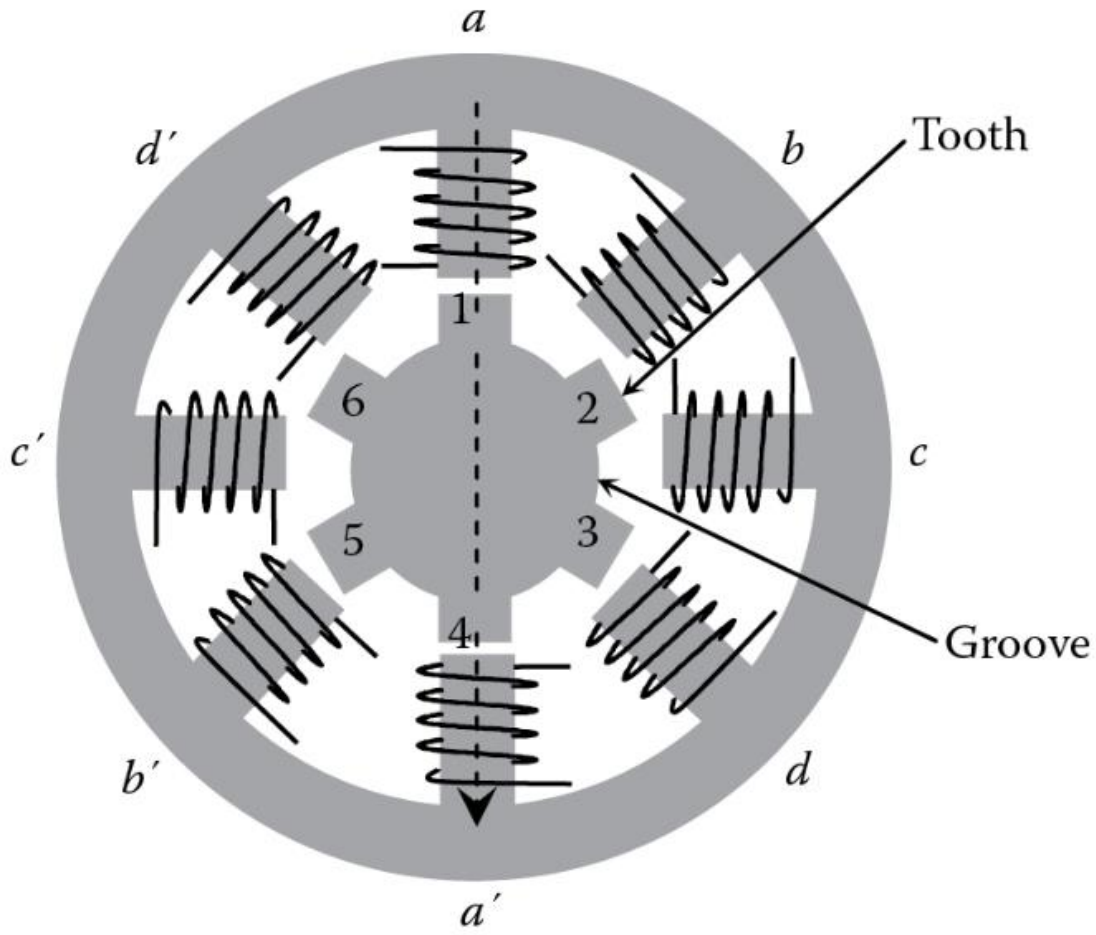
- Stepper motors allow for precise control of rotor position
- Used in robotics and high-precision processes
- Many types of stepper motors
  - Variable reluctance
  - Permanent magnet
  - Hybrid

Stepper Motor Stator



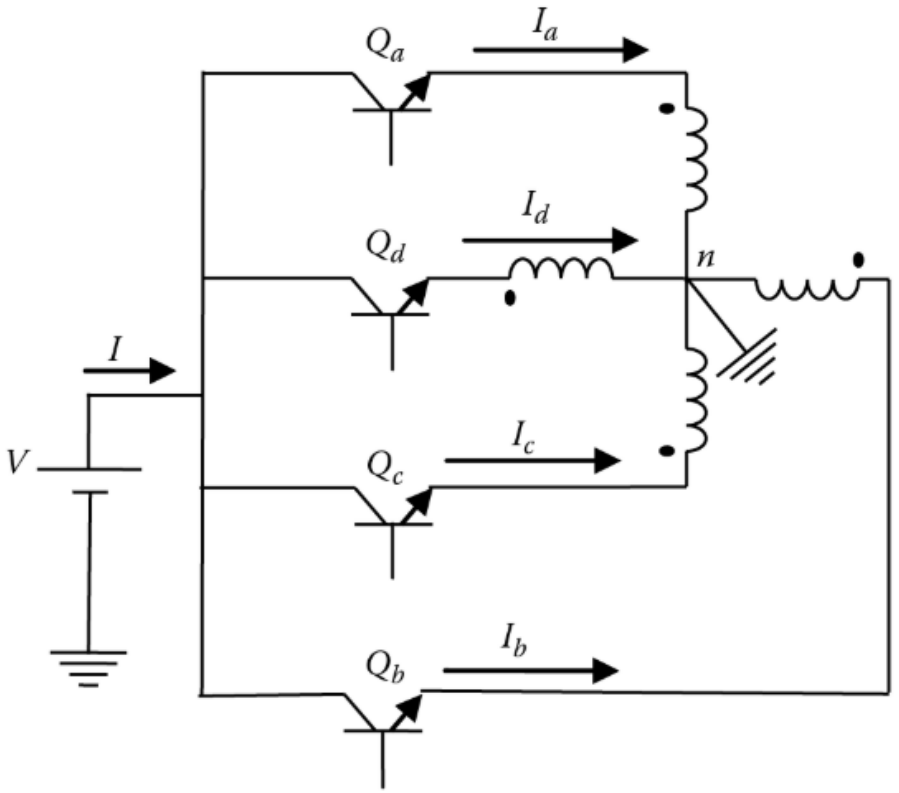


Variable Reluctance Stepper Motor

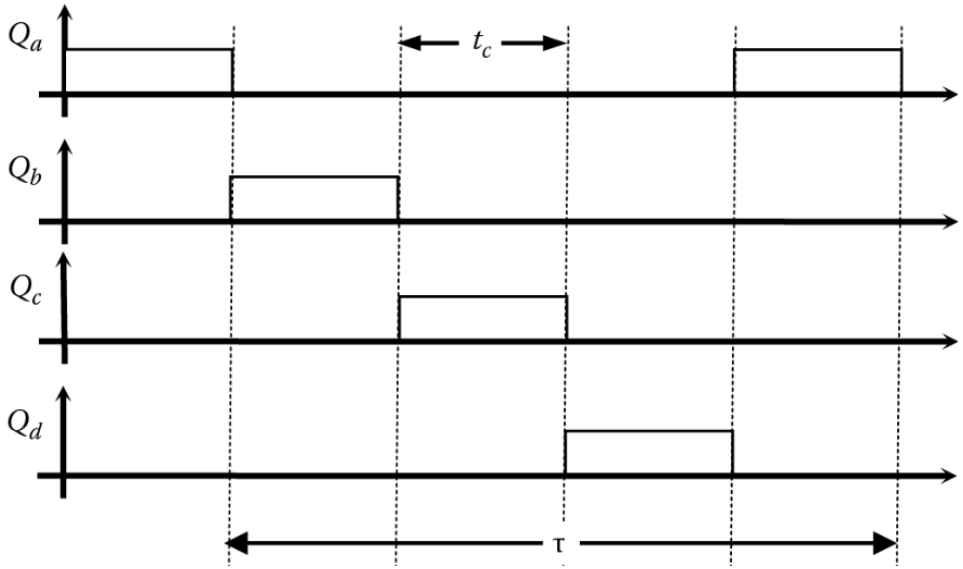


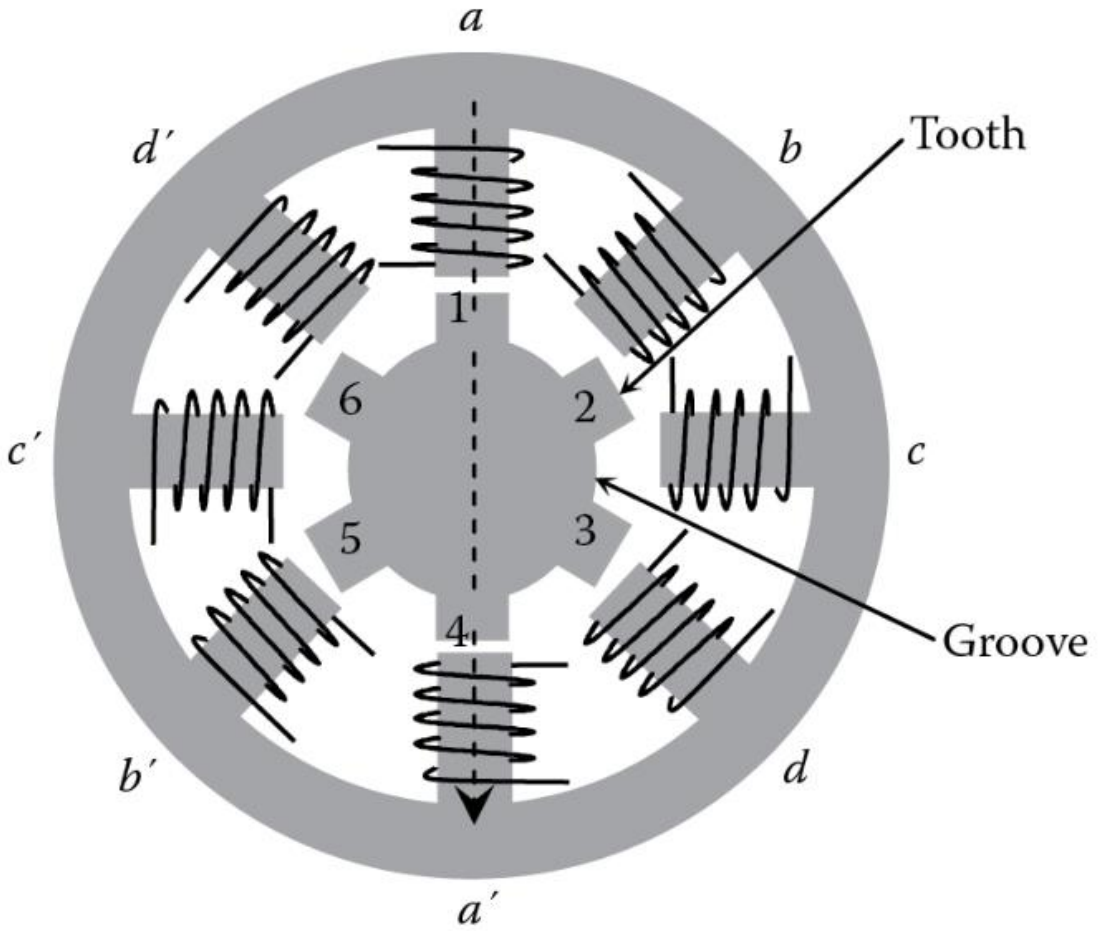
Stator Winding Control

- Switches Q_a, Q_b, … are controlled to energize specific stator coils to achieve
  - desired rotation
  - desired position



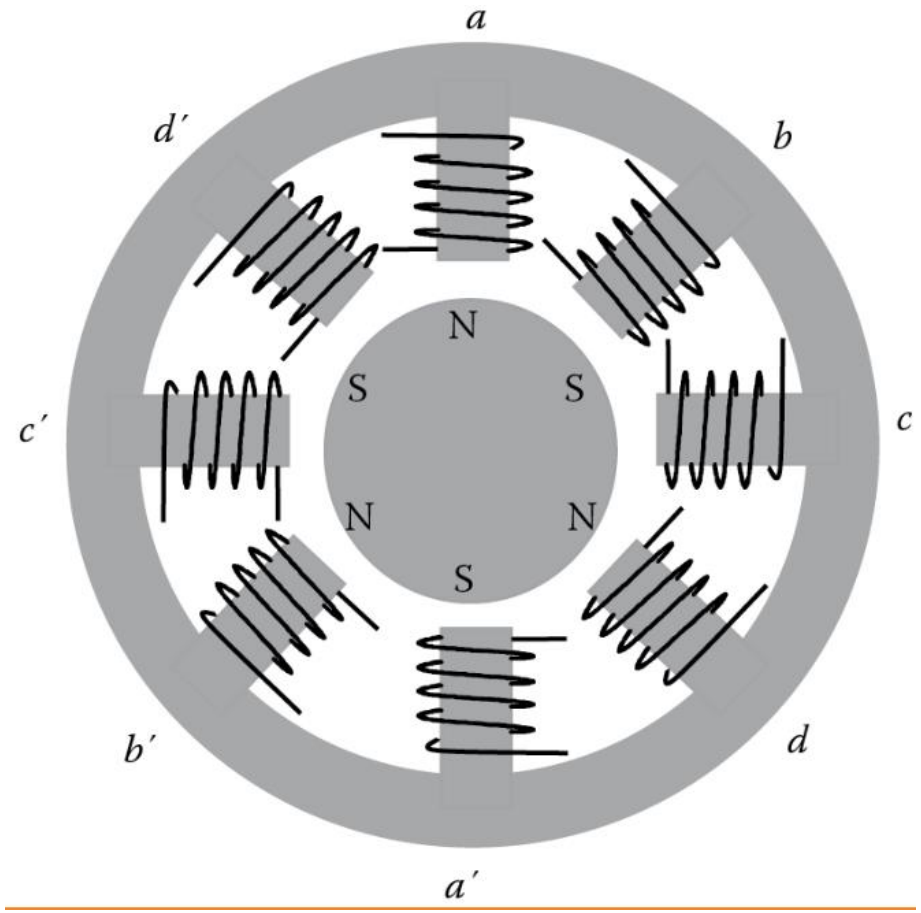
Stepper Motor Control

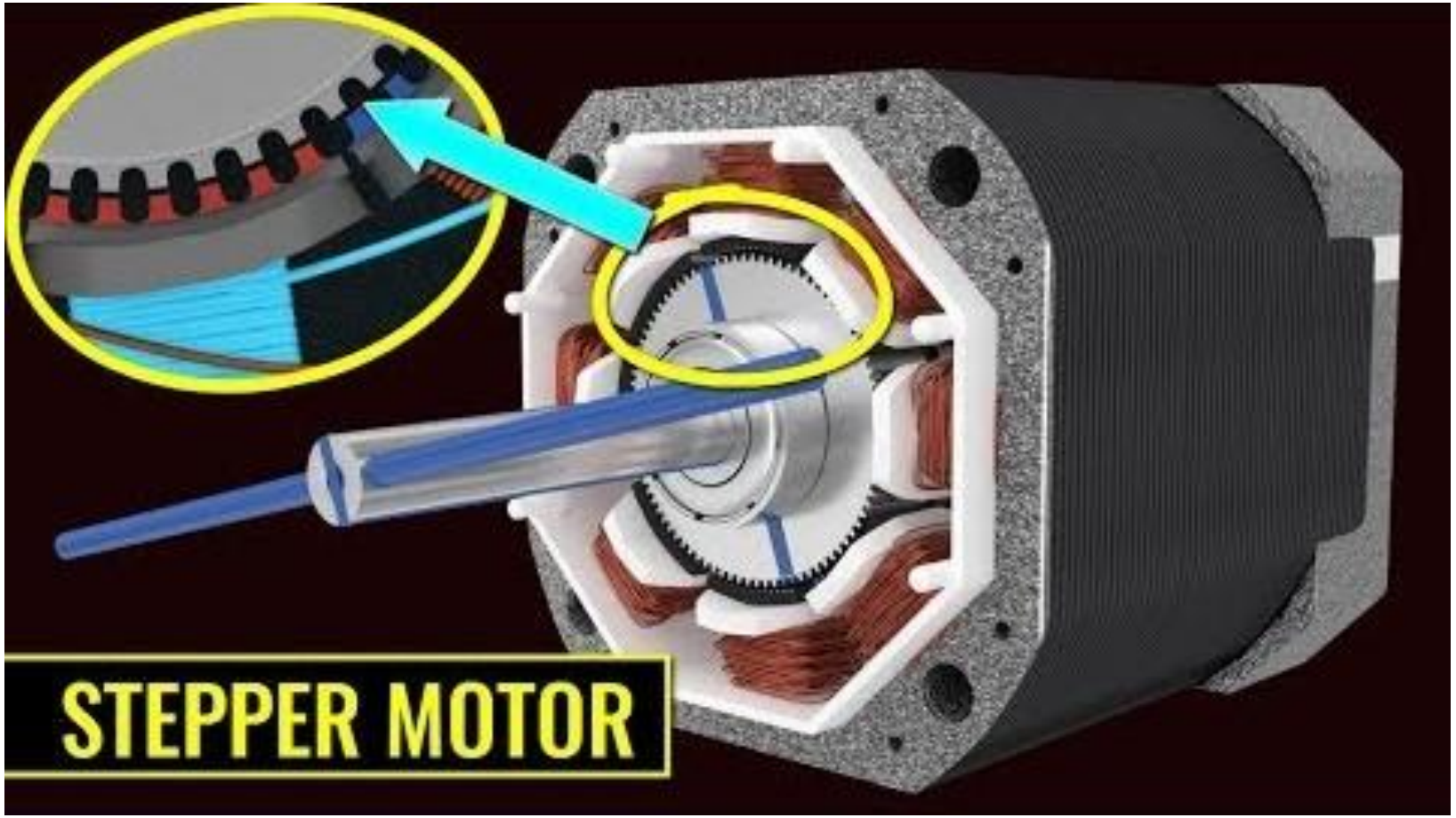




Permanent Magnet Stepper Motor

- Rotor is magnetized
- Provides better holding force and torque than variable reluctance motor
- More expensive
- "Cogging"





https://www.youtube.com/watch?v=eyqwLiowZiU

https://www.youtube.com/watch?v=1_AJkEFk7Zk

Summary

- Induced emf increases with number of poles (for a given mechanical frequency)
- Motors operate by interaction of current flowing in rotor with magnetic field produced by the stator
- Current polarity must be reversed every half-cycle for uni-directional rotation
- Brushes and split ring (commutator) needed for DC output
- Stepper motors are common when open-loop precise position and speed is needed