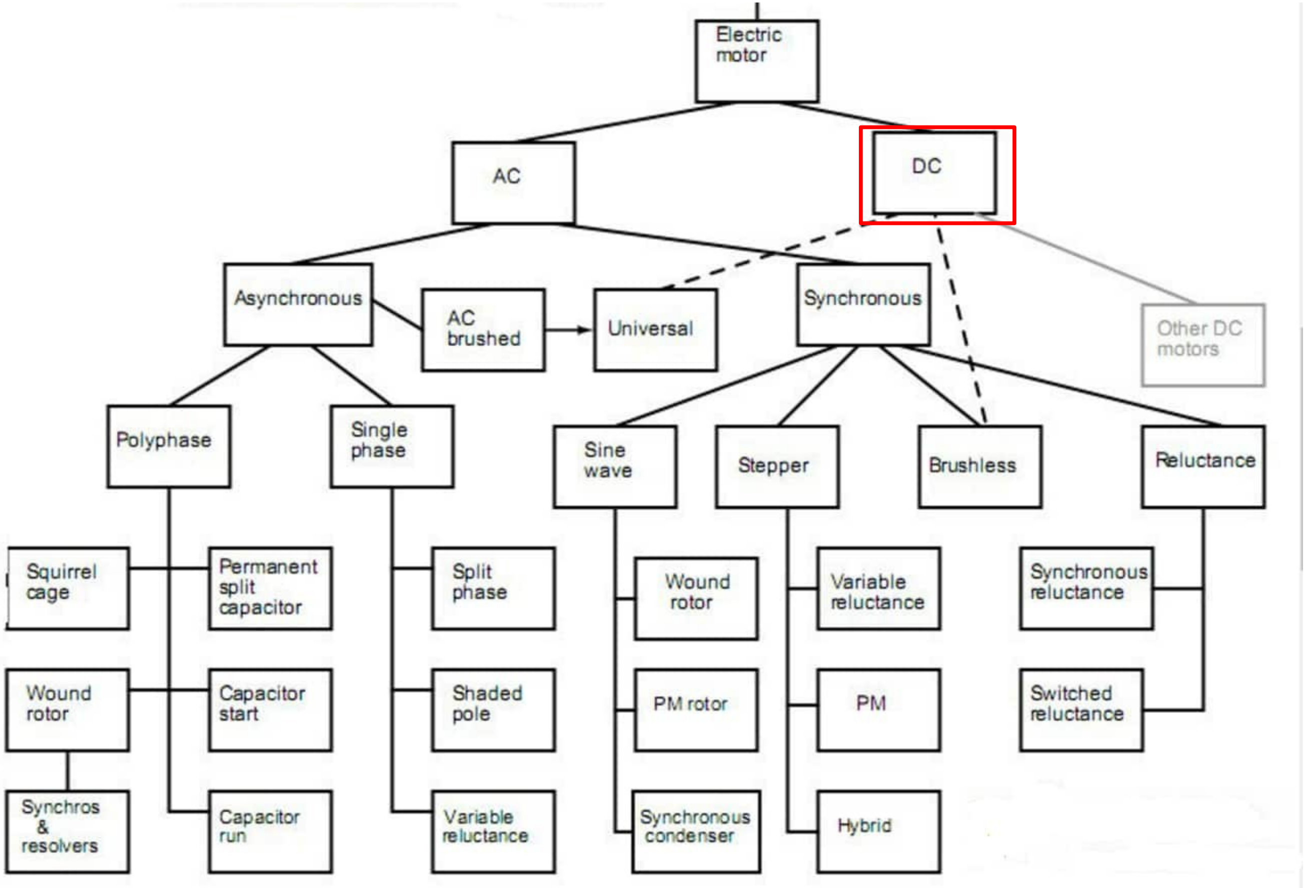
Jacobs University Bremen

Electric motors

DC and universal motors

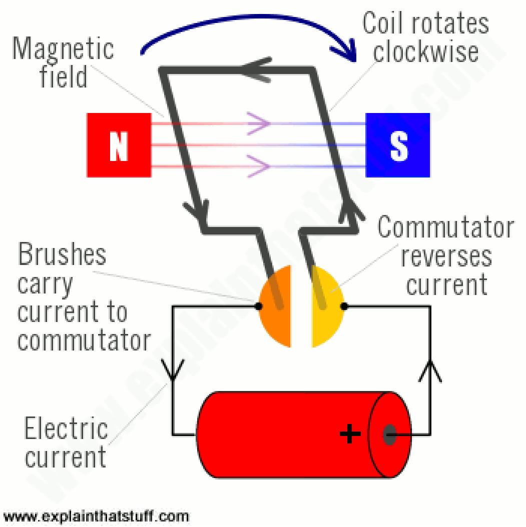
Automation
CO23-320203

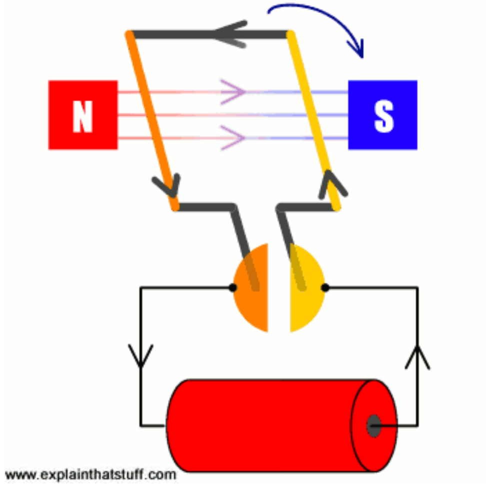
Electric motor family



Brushed DC Motor

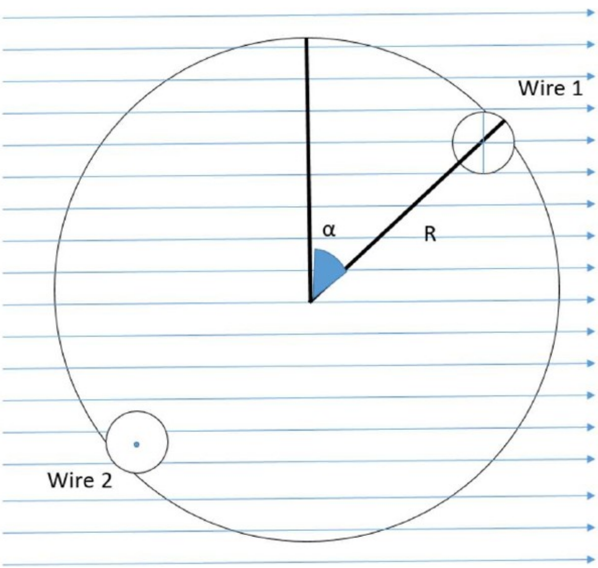
- The basic principle





Brushed DC Motor

- We have tools to do some more in depth calculations



Force (per unit length:)

$$\mathbf{f} = (\mathbf{J}A) \times \mathbf{B}$$
$$= \mathbf{I} \times \mathbf{B}$$

Force magnitude (assuming conductor ⊥ to paper):

$$\mathrm{F} = \mathrm{B\ I\ l}$$

Torque:

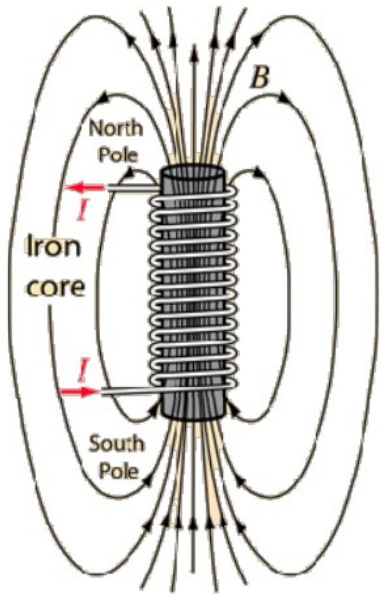
$$\boldsymbol{\tau} = \mathbf{r} \times \mathbf{f}$$

Torque magnitude (given angle α):

$$\tau = \mathrm{RF} \sin \alpha$$

Some background

- What do we know about electromagnets?
- A small magnetic field is produced by the current in the solenoid.
- This small field causes the domains in the iron core to line up
  (the same phenomenon is responsible for hysteresis)
- This leads to a multiplication of the original small magnetic field by a factor of tens to thousands
- A magnetic field of about 1 T can be produced in annealed iron with an external field of about 0.0002 T
- B - Magnetic Flux Density



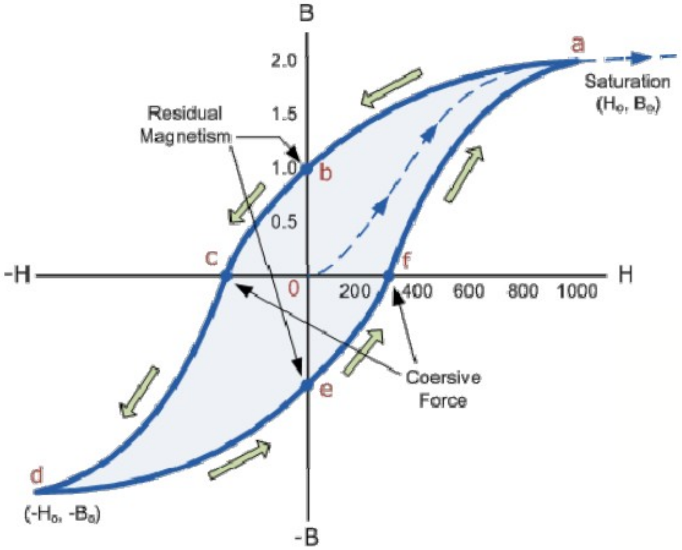
$$B = k \underbrace{\mu_0}_{\mu} n I$$

Relative permeability of iron.
k= 200 for magnetic iron
k= 8000 for mumetal (75% Ni, 2% Cr, 5% Cu, 10% Fe)

with: n - the number of coils per unit length of the solenoids and I - the current flowing through them

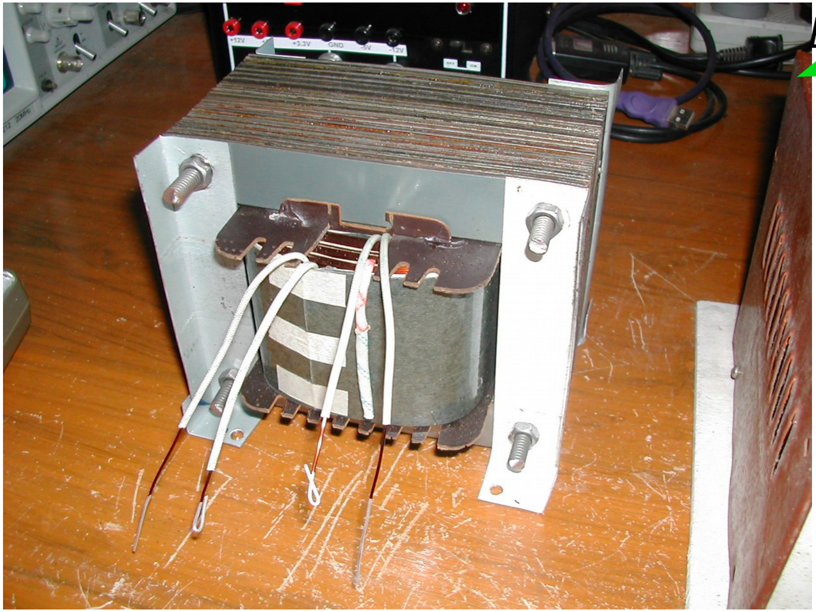
Losses in electromagnets and windings

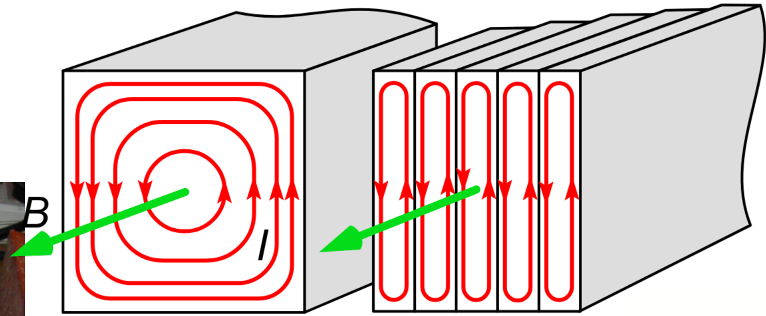
- Hysteresis and eddy current losses are the two main sources of wasted power in the motors
  - Hysteresis in ferromagnetic materials means that the domains "lag" with adapting their arrangements and B rises slower than H
  - Eddy currents are electrons "running around" in the metal core because of the magnetic field and generating Joule heat (that's why the magnetic cores are laminated = composed of thing separated sheets of metal)



Losses in electromagnets and windings

- Example of a laminated transformer core





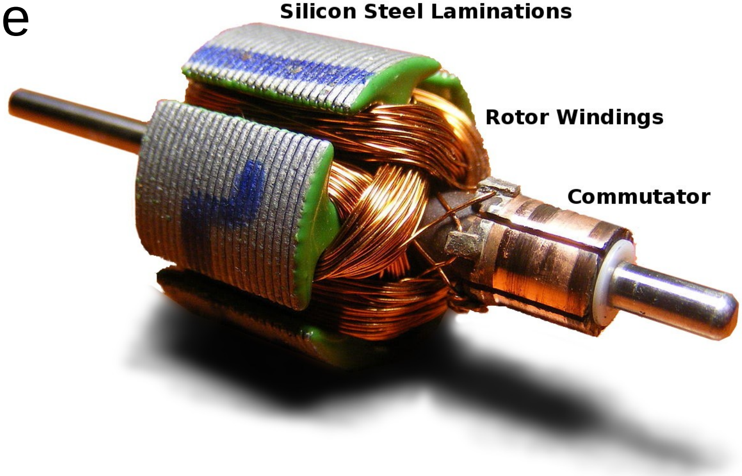
Eddy currents cannot develop beyond the single core sheets while the magnetic field strenghtening effect of soft steel persists.

Losses in electromagnets and windings

- While the previous types of losses are happening in the core of the electromagnet, there are also losses due to the current circulating in the windings due to Joule heating:

$$P \propto I^2 R$$

- Copper has very small resistance but we need many meters of it

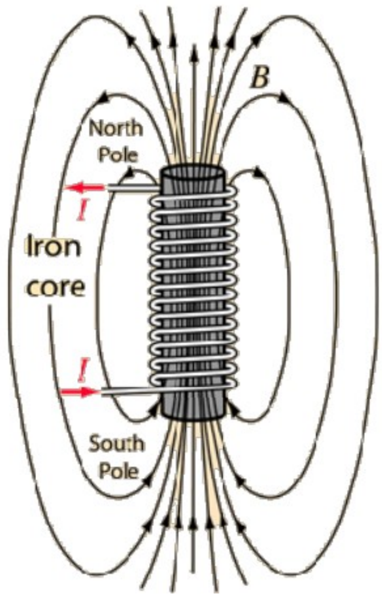


Some background

- Magnetic field is often described in terms of H
- For an isotropic material:

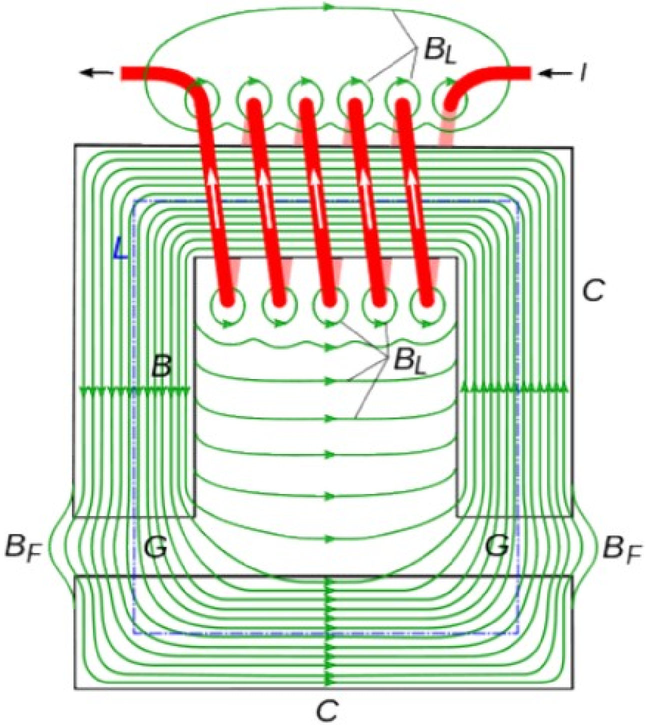
$$\mathbf{B} = \mu\,\mathbf{H}$$

  - H just depends on the current, not the material properties
  - B depends on the material-properties (permeability μ) as well



Some background

- Lines of magnetic-flux form closed-loops:
  - There are no magnetic monopoles
- They take the path of least magnetic resistance (reluctance) and hence concentrate in the iron-core rather than air
  - B_F is the fringing effect in the air-gap
  - B_L is the leakage flux
- The air-gap flux is created by the magnetomotive force of the coil and can be used to create an approximately constant B field for a rotor, for example



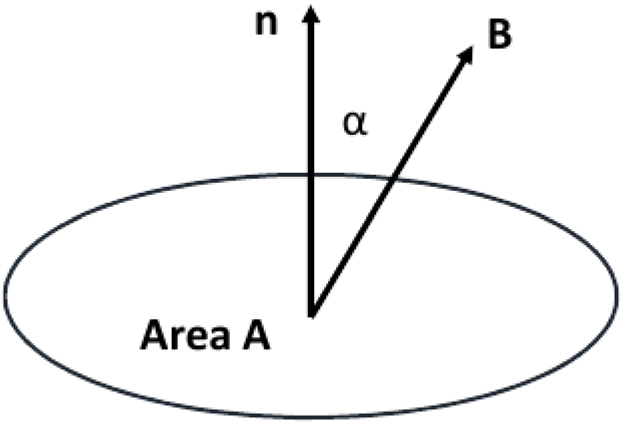
More on magnetic flux

- From magnetic flux density to flux
  - Flux φ (unit Weber) passing through a surface-area S

$$\phi = \oint_S \mathbf{B} \cdot d\mathbf{s}$$

  - If the flux-density B is constant for the whole area A (with normal n) , and inclined at an angle α to it:

$$\phi = \mathbf{B} \cdot \mathbf{A}$$
$$= B\,A\,\cos\alpha$$



Ampere's law revisited

- For any closed path, the integral of the tangential component of H around the closed loop is equal to the current enclosed by the path

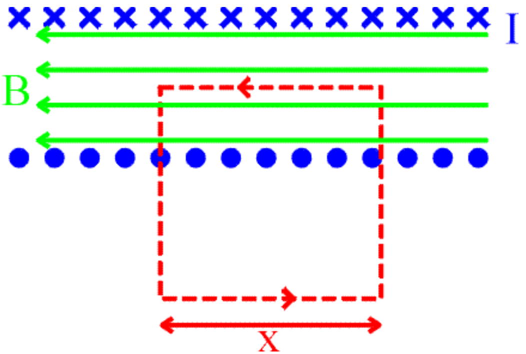
$$\oint_L \mathbf{H} \cdot d\ell = N I$$

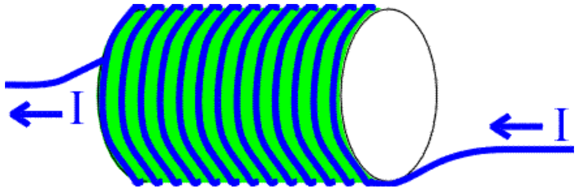
where N is the number of (for example) solenoid conductors carrying current inside the path and I [A] is the current flowing through them

- Hence, for a coil:

$$\oint_L \mathbf{H} \cdot d\ell = H\,L = N\,I$$

$$H = \frac{N\,I}{L} = n\,I$$





Magnetic vs electric circuit

- Here is an analogy helpful in understanding

Electric Circuit	Magnetic Circuit
Path traced by the current is known as electric current.	Path traced by the magnetic flux is called as magnetic circuit.
EMF is the driving force in the electric circuit. The unit is Volts.	MMF is the driving force in the magnetic circuit. The unit is ampere turns.
There is a current I in the electric circuit which is measured in amperes.	There is flux φ in the magnetic circuit which is measured in the weber.
The flow of electrons decides the current in conductor.	The number of magnetic lines of force decides the flux.

Resistance (R) oppose the flow of the current. The unit is Ohm	Reluctance (S) is opposed by magnetic path to the flux. The Unit is ampere turn/weber.
$R = \rho . l/a$. Directly proportional to l. Inversely proportional to a. Depends on nature of material.	$S = l/ (\mu_o \mu_r a)$. Directly proportional to l. Inversely proportional to $\mu = \mu_o \mu_r$. Inversely proportional to a
The current I = EMF/ Resistance	The Flux = MMF/ Reluctance
The current density	The flux density
Kirchhoff current law and voltage law is applicable to the electric circuit.	Kirchhoff mmf law and flux law is applicable to the magnetic flux.

Theory applied to motors

- We can revisit the example of the coil of the rotor armature in the magnetic field:

$$\boldsymbol{\tau} = -\frac{DL}{A}(AB)\, I\, \sin\alpha\, \hat{\mathbf{z}}$$

$$\text{Flux } \phi = A\, B$$

$$\|\boldsymbol{\tau}\| = K_\phi\, \phi\, I\, \sin\alpha,$$

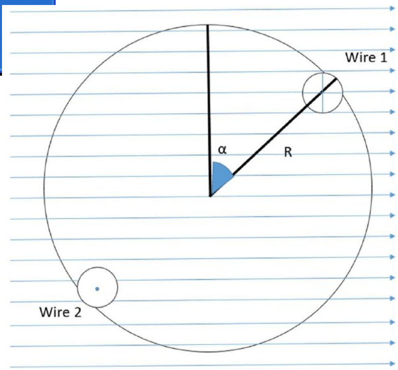
with K_ϕ being a motor-specific constant:

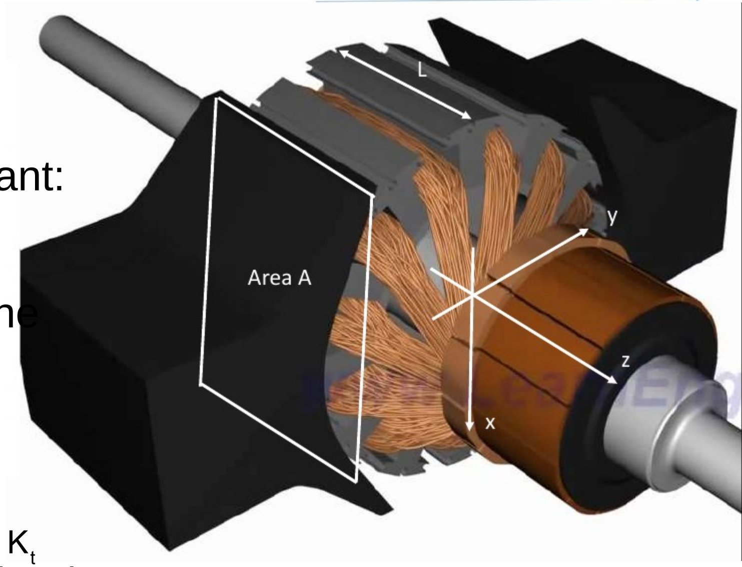
$$K_\phi \triangleq \frac{DL}{A}$$

- For multiple windings, the effect of the angle is cancelled out:

$$\|\boldsymbol{\tau}\| = \boxed{K_\phi\, \phi} I$$

This part is fixed for permanent magnet-based motors and can be integrated into K_t

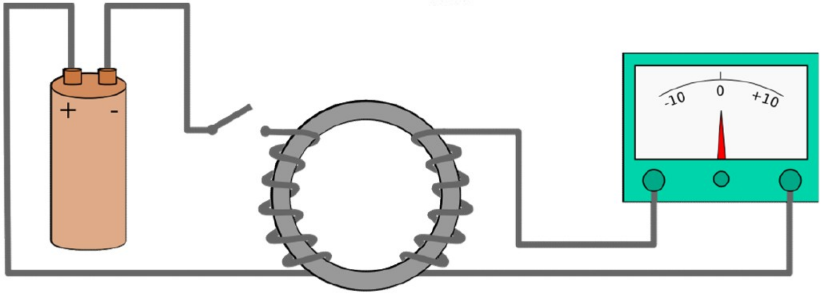




Back EMF

- Faraday's law of induction
  - A change in magnetic flux ϕ passing through the coils induces an EMF and causes an electromotive force e

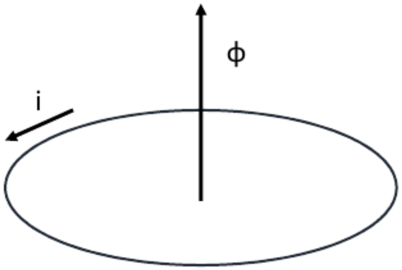
$$e = -\frac{d\phi}{dt}$$



  - Motors have plenty of coils traveling in a magnetic flux and are subject to this law

Back EMF

- Lenz's Law (which direction will the Faraday's law work in?)
  - The direction of the current induced in a conductor by a changing magnetic field is such that it will create a field that opposes the change that produced it.



Flux ϕ is decreasing

  - For N loops: $$e = -N\frac{d\phi}{dt}$$

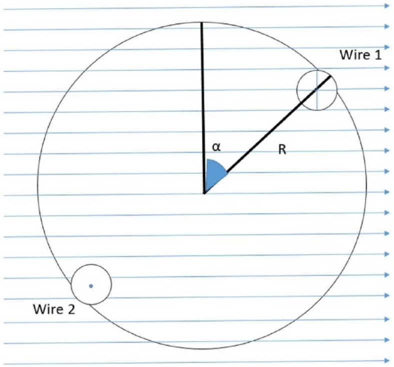
Back EMF

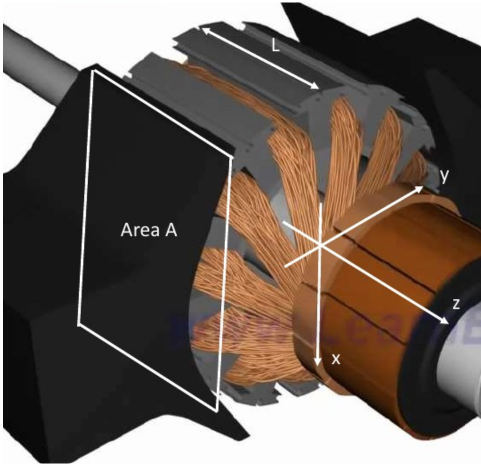
- What is the flux passing through the winding of area a=DL when it is at an angle α to B?

$$\phi = \mathbf{B} \cdot \mathbf{a}$$

(the direction of the area-vector a is normal to the plane of the loop)

$$\phi = B\,a\,\cos\alpha$$
$$= B\,L\,D\,\cos\alpha$$





- We call this induced electric potential back electromotive force (back EMF)

$$e = -\frac{d\phi}{dt} = B\,DL\,\dot{\alpha}\,\sin\alpha = BA\,\frac{DL}{A}\,\omega\,\sin\alpha$$
$$e = K_\phi\,\phi\,\omega$$

Electric motor's equations

- We have established the essential physics of a motor

$$\|\boldsymbol{\tau}\| = K_\phi \, \phi \, I$$

Torque is proportional to the current and the applied flux!

$$e = K_\phi \, \phi \, \omega$$

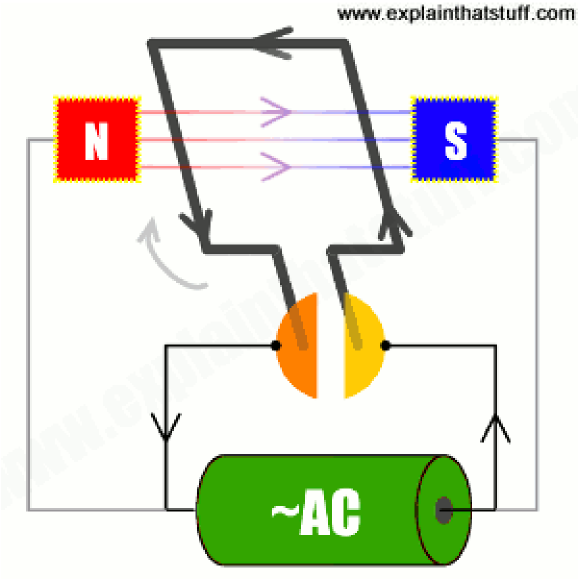
$$K_\phi \triangleq \frac{DL}{A}$$

Induced Back-EMF is proportional to the angular-speed and the applied flux!

- The applied flux ϕ can be produced in two different ways depending on the type of the DC motor:
  - by the permanent magnets in the stator
  - by the Field-Coils in Shunt and Series DC motors

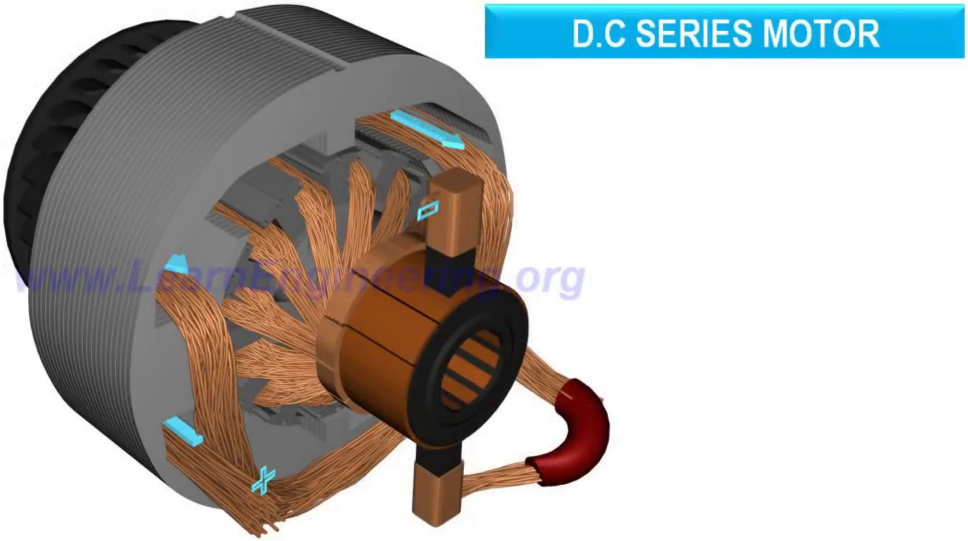
Universal Motor

- The basic principle
  - What if we replace the fixed magnet by an electromagnet?



Universal Motor

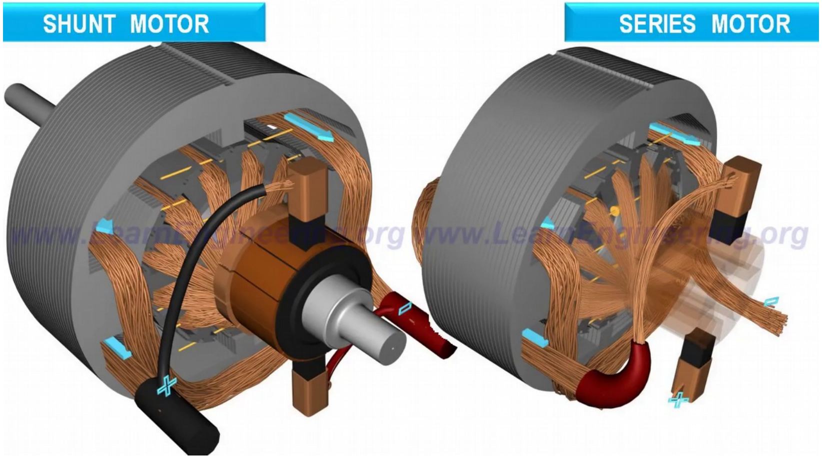
- The basic principle



"How do Universal Motors work ?"
https://www.youtube.com/watch?v=0PDRJKz-mqE

Universal Motor

(recall the principle and construction of the DC motor from last lecture)



"DC Motor, How it works?"
https://www.youtube.com/watch?v=LAtPHANEfQo