Topic 8: electromagnetism

Content:

- laws of electromagnetic interaction:

a. Lorentz force (law)
b. Biot-Savart law
c. Amper’s law
d. Faraday’s law of induction

- comments to units

- laws of electromagnetic interaction

- laws of electromagnetic interaction

These laws describe the relation between electric and magnetic field in their

common interaction (so called electromagnetic forse).

We know following basic EM laws:

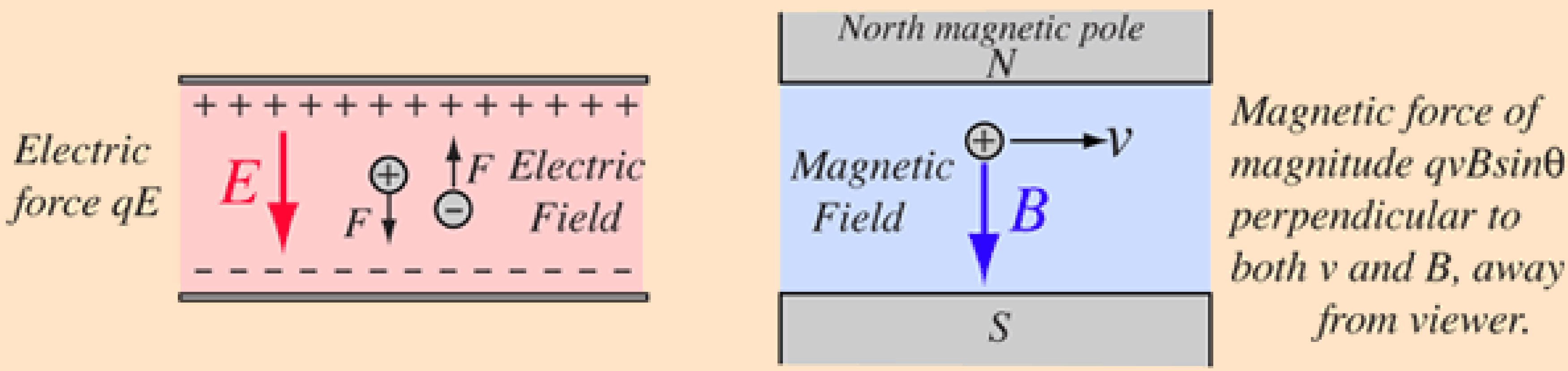
Lorentz force (law), Biot-Savart' law, Ampere's law, Faraday's law and Lenz' law.

Lorentz force (law)

If a particle of charge q moves with velocity $\boldsymbol{v}$ in the presence of an electric field $\boldsymbol{E}$ and a magnetic field $\boldsymbol{B}$, then it will experience a force:

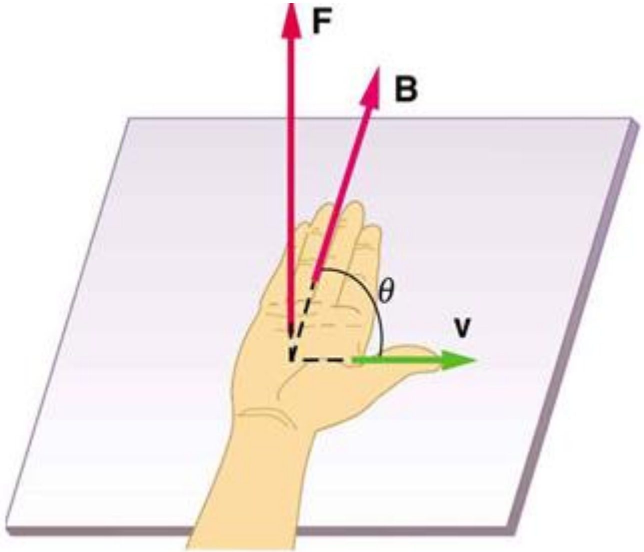
$$\vec{F} = \underbrace{q\vec{E}}_{\text{Electric force}} + \underbrace{q\vec{v}\,x\,\vec{B}}_{\text{Magnetic force}}$$

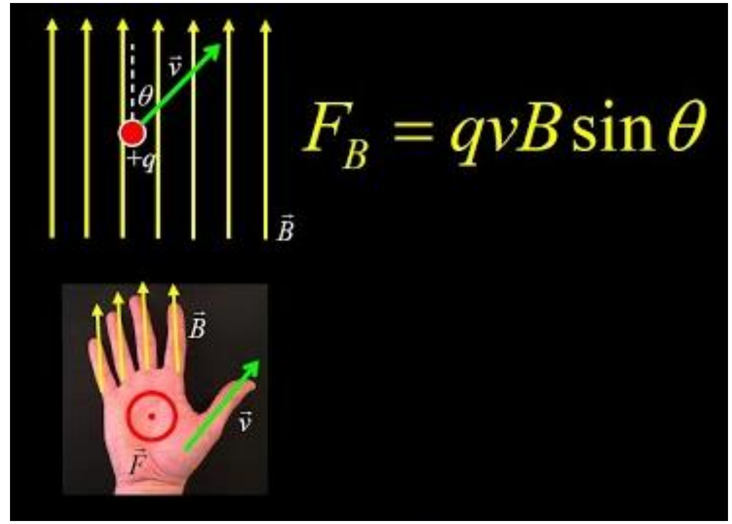
The electric force is straightforward, being in the direction of the electric field if the charge q is positive, but the direction of the magnetic part of the force is given by the right hand rule.



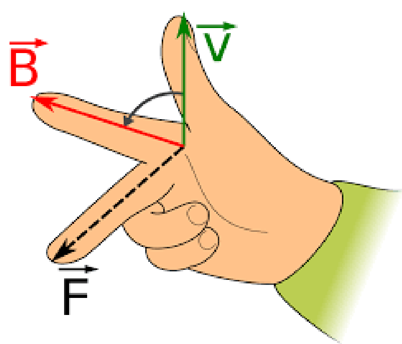
Important: so called right hand rule for the magnetic force.

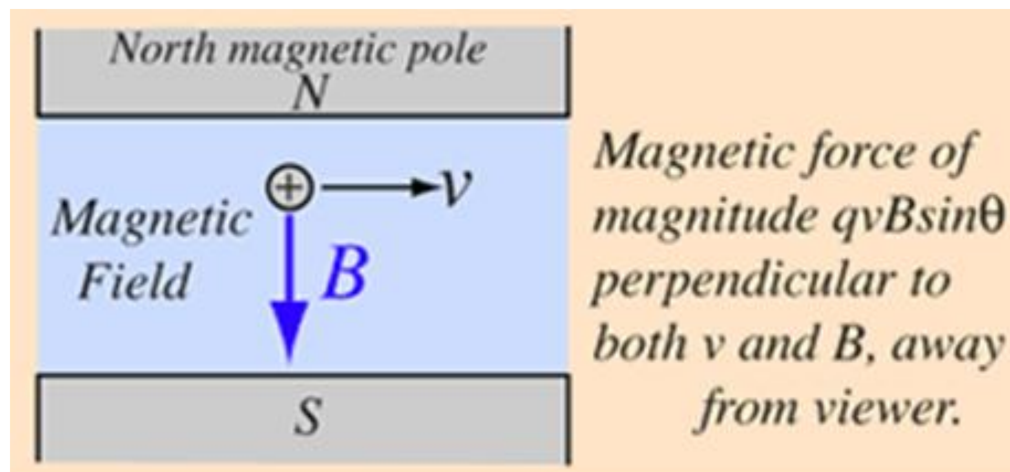
Important: so called right hand rule for the magnetic force.





OR



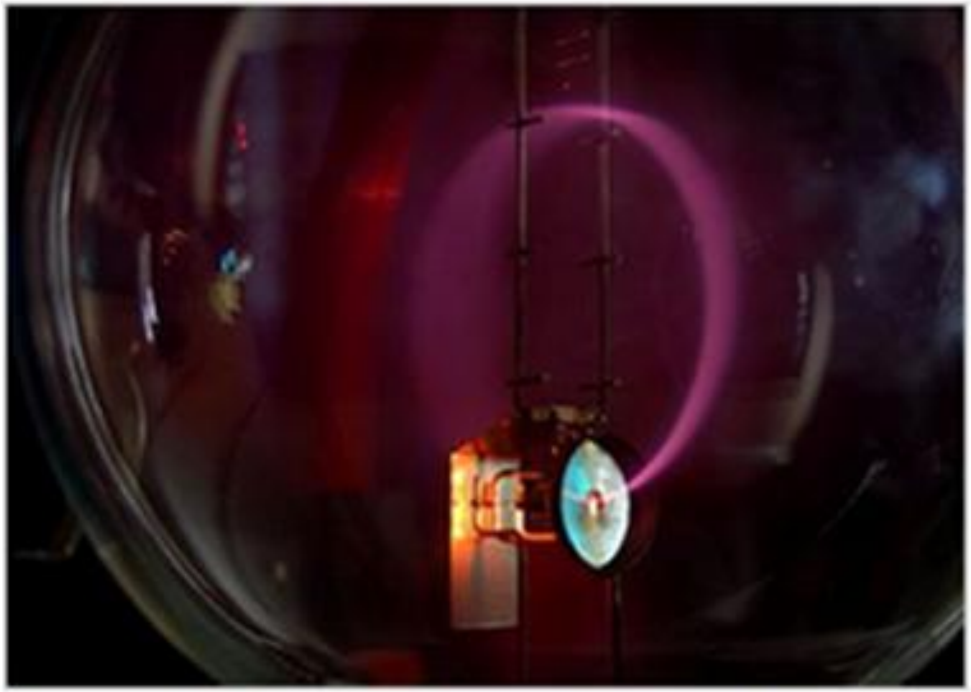


Used symbols: $\odot$ - vector points out of the screen

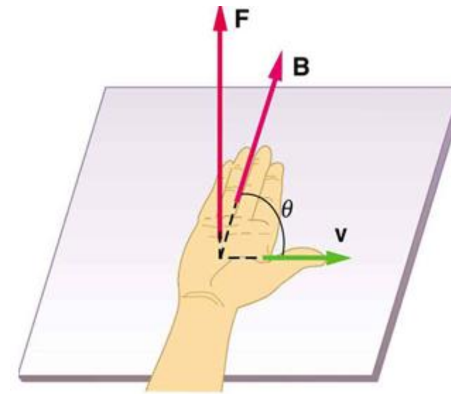
$\oplus$ - vector points inside the screen

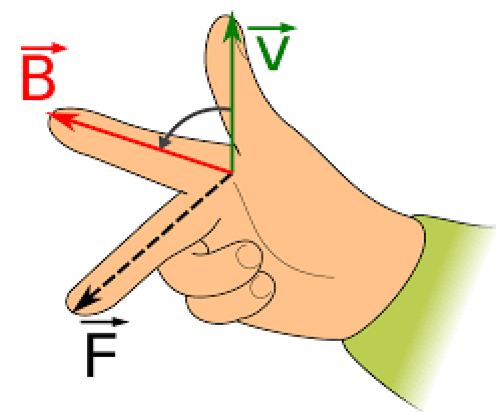
Lorentz force (law)

$$\vec{F} = \underbrace{q\vec{E}}_{\text{Electric force}} + \underbrace{q\vec{v} \times \vec{B}}_{\text{Magnetic force}}$$



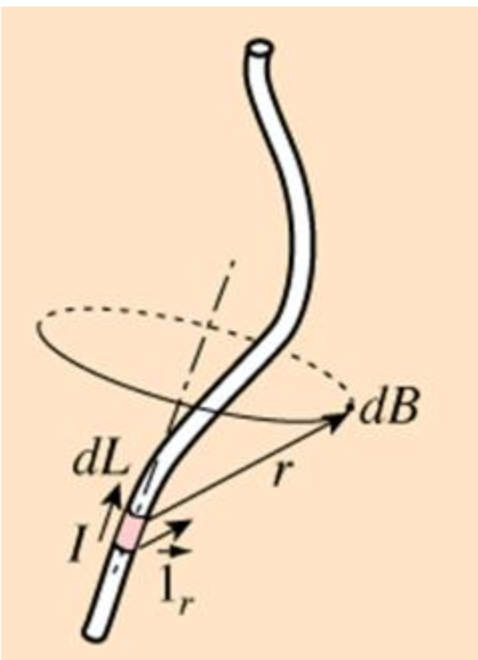
Beam of electrons moving in a circle, due to the presence of a magnetic field. Purple light is emitted along the electron path, due to the electrons colliding with gas molecules in the bulb.





Biot-Savart law

The Biot-Savart Law relates magnetic fields to the currents, which are their sources. In a similar manner, Coulomb's law relates electric fields to the point charges which are their sources (finding the magnetic field resulting from a current distribution involves the vector product).



From empirism we know: $$\left|dB\right| = K\frac{I}{r^2}$$

Resulting field **B** we get as a result of integration along the wire.

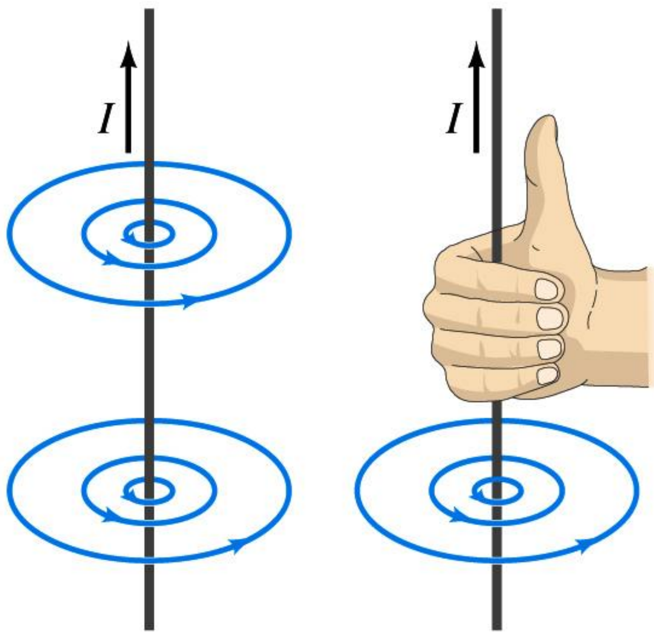
$$\left|\vec{B}\right| = \frac{\mu_0}{2\pi}\frac{I}{r}$$

Biot-Savart law

Result after integration (for a direct wire):

$$\boxed{\left|\vec{B}\right| = \frac{\mu_0}{2\pi}\frac{I}{r}}$$

here *r* is the perpendicular distance from a direct wire (with direct current *I*)



(a) (b)

Here we have a next right hand rule – showing the direction of **B**.

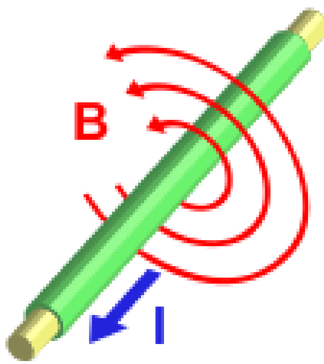
Biot-Savart law

The video from the lecture on magnetism:
https://www.youtube.com/watch?v=opJYLFvI-RE

Next nice video:
https://www.youtube.com/watch?v=mxwevNEa2vs

Amper's law (as a consequence of Biot-Savart law)

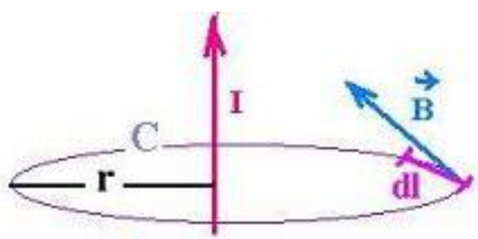
Also called as Amper's circuital law.



$$\boxed{\oint_{l(S)} \vec{B}\cdot d\vec{l} = \mu_0 I}$$

Derivation:

Along a circle the angle between these two vectors (**B** and d**l**) is zero, so it follows:



$$\oint_{l(S)} \vec{B}\cdot d\vec{l} = \oint_{l(S)} \left|\vec{B}\right| dl = \left|\vec{B}\right| 2\pi r = \mu_0 I$$

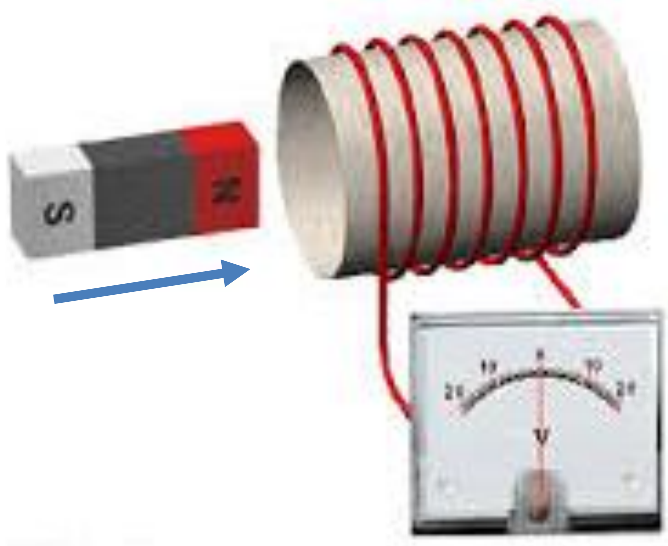
$$\left|\vec{B}\right| = \frac{\mu_0}{2\pi}\frac{I}{r}$$

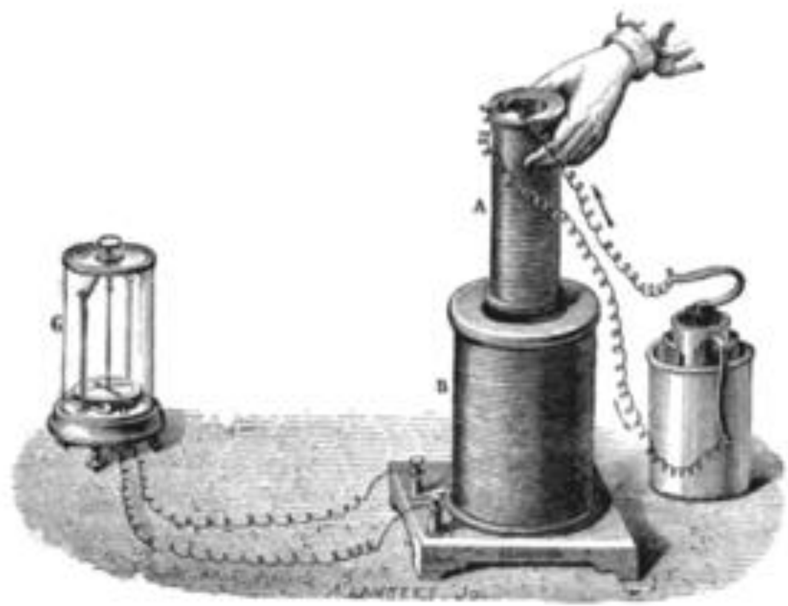
r - radius of the circle (around the wire with *I*)

When we now enter for the size of vector **B** the Biot-Savart law expression, we get the final result.

Faraday’s law of induction

Faraday’s Law of Induction describes how an electric current produces a magnetic field and, conversely, how a changing magnetic field generates an electric current in a conductor.
English physicist Michael Faraday gets the credit for discovering magnetic induction in 1830; however, an American physicist, Joseph Henry, independently made the same discovery about the same time.





Faraday’s law of induction (experiment):
https://www.youtube.com/watch?v=vwIdZjjd8fo

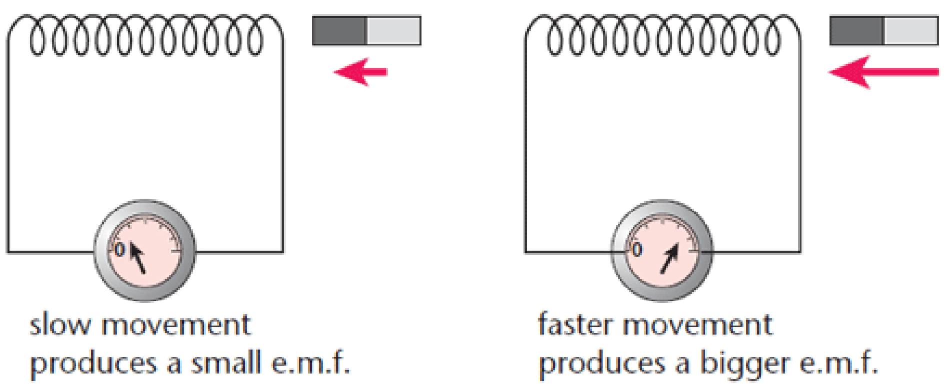
Faraday’s law of induction

Quantitative aspects of Faraday’s law of induction describe the change of the magnetic flux with time – it is equal to the electromotive force $\mathcal{E}$ (EMF), measured in volts (!):

$$\boxed{\varepsilon = \mathrm{Emf} = -\frac{d\Phi_B}{dt}}$$

unit: [W/s = V·s/s = V]

The direction of the electromotive force is given by Lenz's law.



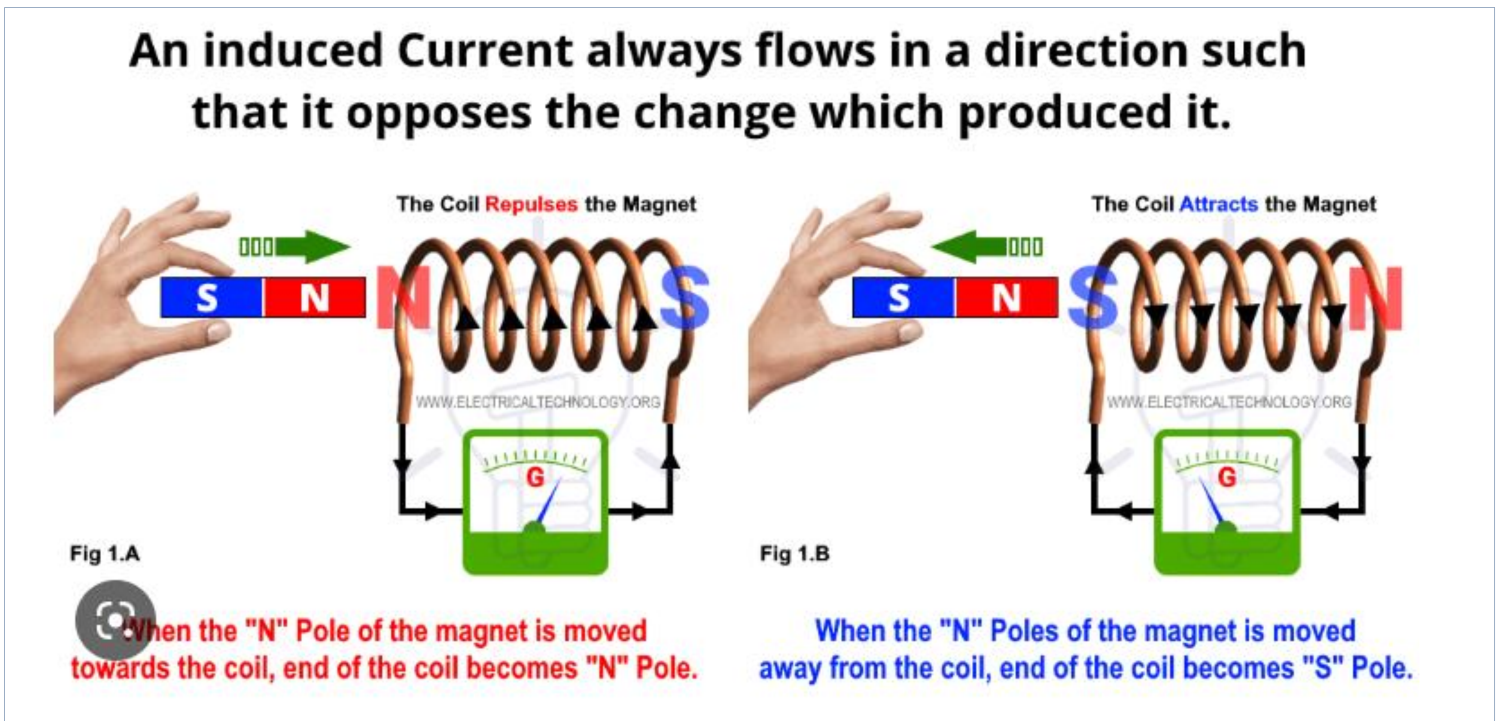
Comment: The word "force" is somewhat misleading, because EMF is not a force, but rather a "potential" to provide energy.

An electromotive force can be originated also in a situation, when a conductor is moving in a magnetic field – principle of a dynamo.

Faraday’s law of induction
(Lenz’s law)

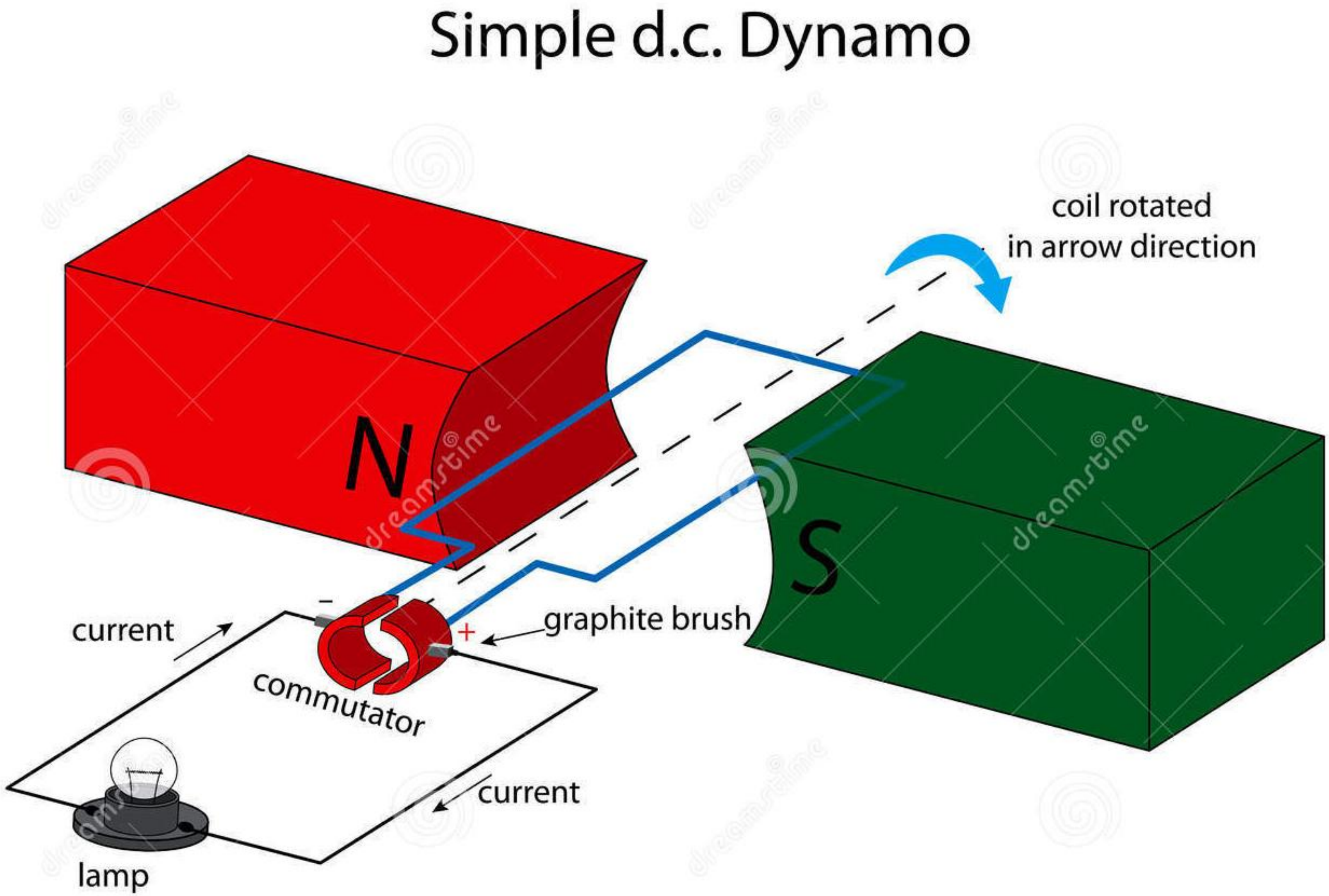
The direction of the electromotive force is given by Lenz's law:

Lenz’s law of electromagnetic induction states that the direction of the current induced in a conductor by a changing magnetic field is such that the magnetic field created by the induced current <u>opposes the initial changing magnetic field</u> which produced it.

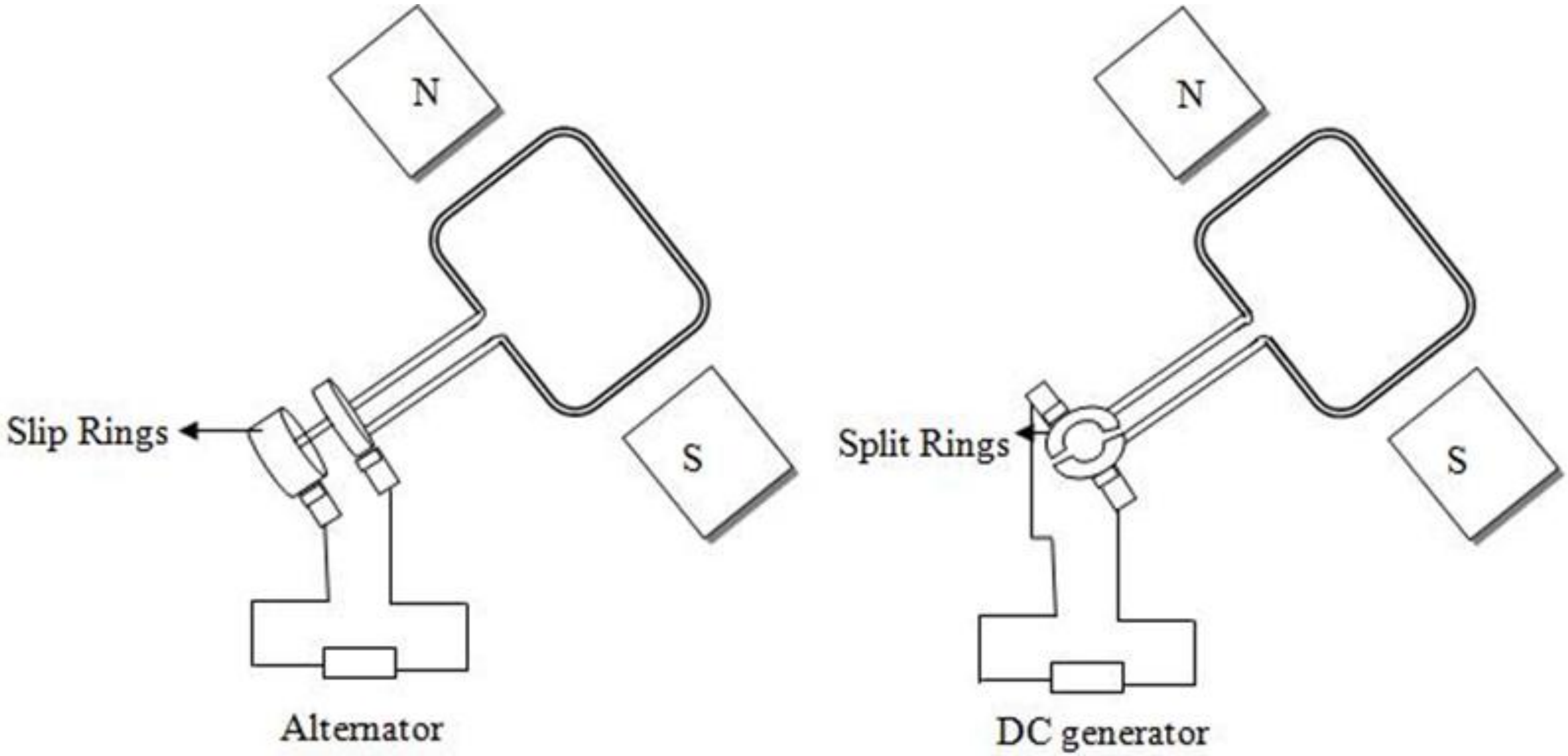


Faraday’s law of induction

An electromotive force can be originated also in a situation, when a conductor is moving in a magnetic field – principle of a dynamo.

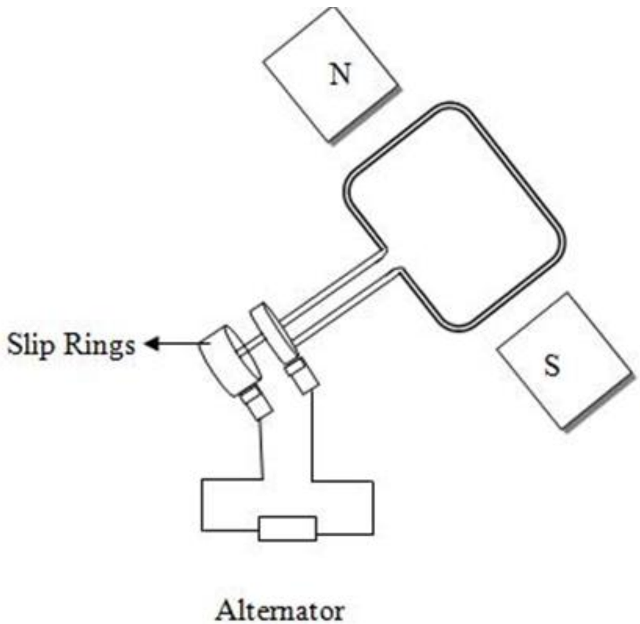


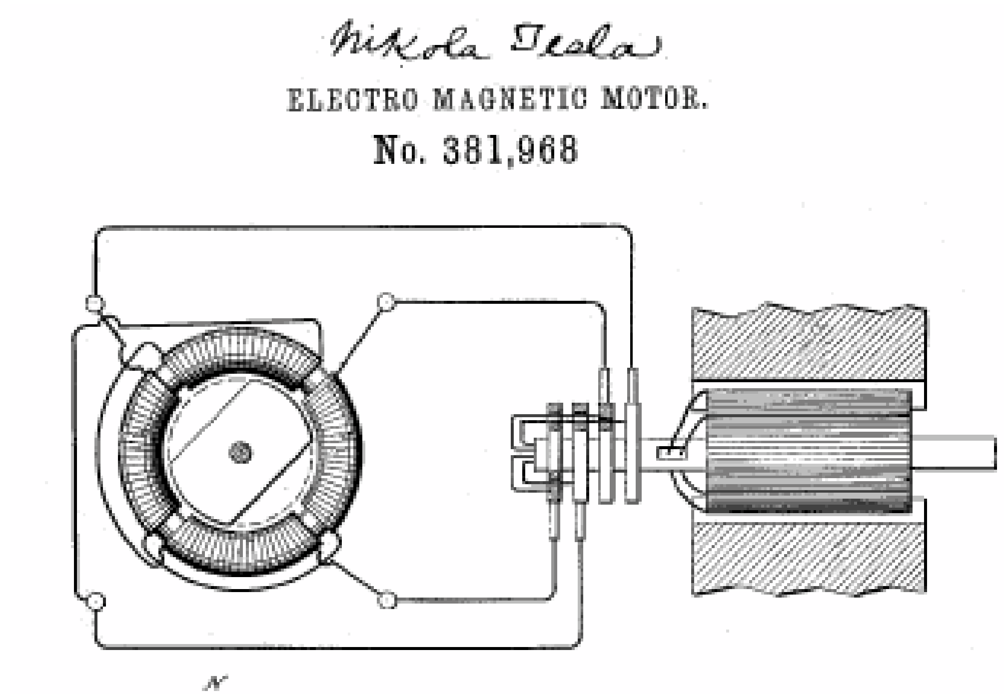
Faraday’s law of induction



Difference between a DC dynamo (DC generator) and AC dynamo (alternator) is the shape of the commutator.
In the case of DC dynamo it has split rings – to obtain the current of only one direction. An AC dynamo has slip rings.

Faraday’s law of induction





Next very important contribution of Nicola Tesla:
He suggested the use of so called rotating magnetic field in the case of the commutator (there was no need for the use of brushes).
Result was the invention of so called induction motor.

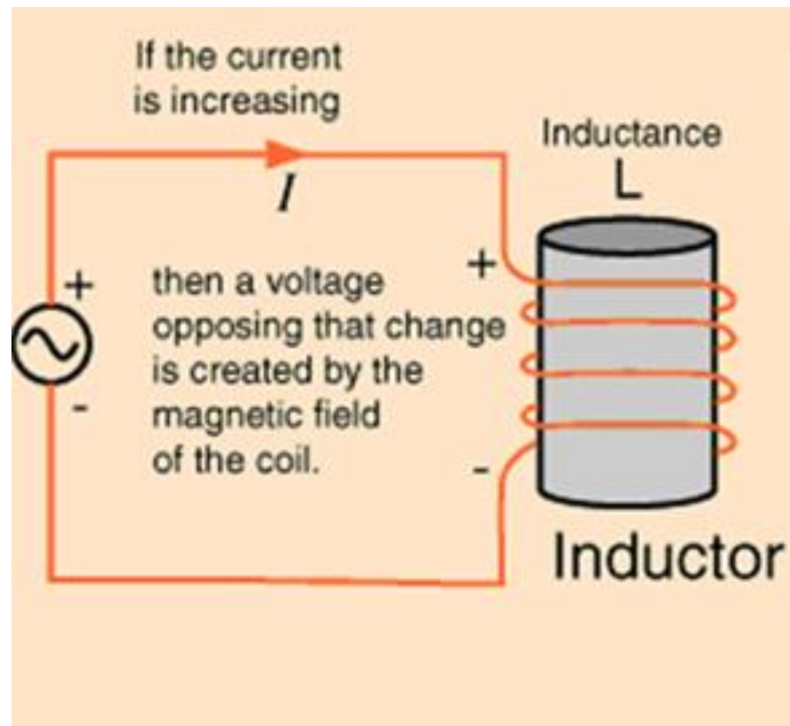
Faraday's law of induction - inductance

Inductance (L)

Inductance is the tendency of an electrical conductor to oppose a change in the electric current flowing through it
(conductor is often in the shape of a coil).
It is connected with the Electromotive force (Emf):

$$\boxed{\mathrm{Emf} = -\mathrm{L}\frac{\Delta \mathrm{I}}{\Delta \mathrm{t}}}$$

unit for L: [V·s/A] = [Henry]



Lecture 6: magnetism, electromagnetism

- comments to units

unit Weber

Unit of magnetic flux Φ_B .

A change in flux of one weber per second will induce an electromotive force of one volt (produce an electric potential difference of one volt across two open-circuited terminals).
The unit was named after Wilhelm Eduard Weber, a German physicist.
As an SI derived unit, the weber can also be expressed as:

$$\mathrm{Wb} = \frac{\mathrm{kg}\cdot\mathrm{m}^2}{\mathrm{s}^2\cdot\mathrm{A}} = \mathrm{V}\cdot\mathrm{s} = \mathrm{T}\cdot\mathrm{m}^2 = \frac{\mathrm{J}}{\mathrm{A}}$$

---

unit Farad

Unit of electrical capacitance.

It describes the ability of a body to store an electrical charge, it is equivalent to 1 coulomb per volt (C/V).
Named after the English physicist Michael Faraday (1791–1867).

$$\mathrm{F} = \frac{\mathrm{s}^4\cdot\mathrm{A}^2}{\mathrm{m}^2\cdot\mathrm{kg}} = \frac{\mathrm{s}^2\cdot\mathrm{C}^2}{\mathrm{m}^2\cdot\mathrm{kg}} = \frac{\mathrm{C}}{\mathrm{V}} = \frac{\mathrm{A}\cdot\mathrm{s}}{\mathrm{V}} = \frac{\mathrm{W}\cdot\mathrm{s}}{\mathrm{V}^2} = \frac{\mathrm{J}}{\mathrm{V}^2} = \frac{\mathrm{N}\cdot\mathrm{m}}{\mathrm{V}^2} = \frac{\mathrm{C}^2}{\mathrm{J}} = \frac{\mathrm{C}^2}{\mathrm{N}\cdot\mathrm{m}} = \frac{\mathrm{s}}{\Omega} = \frac{1}{\Omega\cdot\mathrm{Hz}} = \frac{\mathrm{S}}{\mathrm{Hz}} = \frac{\mathrm{s}^2}{\mathrm{H}}$$

unit Tesla

Unit of magnetic induction **B**.
A particle, carrying a charge of one coulomb, and passing through a magnetic field of one tesla, at a speed of one metre per second, perpendicular to said field, experiences a force with magnitude one newton, according to the Lorentz force law.

One tesla is equal to one weber per square metre. The unit was announced during the General Conference on Weights and Measures in 1960 and is named in honour of Nikola Tesla.
As an SI derived unit, the tesla can also be expressed as:

$$\mathrm{T} = \frac{\mathrm{V}\cdot\mathrm{s}}{\mathrm{m}^2} = \frac{\mathrm{N}}{\mathrm{A}\cdot\mathrm{m}} = \frac{\mathrm{Wb}}{\mathrm{m}^2} = \frac{\mathrm{kg}}{\mathrm{C}\cdot\mathrm{s}} = \frac{\mathrm{N}\cdot\mathrm{s}}{\mathrm{C}\cdot\mathrm{m}}$$

In the older system CGS:

- The cgs unit is a *Gauss* (G)
  - 1 T = 10^4 G

unit Henry

Unit of electrical inductance L.
The inductance of an electric circuit is one henry when an electric current that is changing at one ampere per second results in an electromotive force of one volt across the inductor.
The unit was named in honour of Joseph Henry, an American physicist.
As an SI derived unit, the henry can also be expressed as:

$$\mathrm{H} = \frac{\mathrm{kg}\cdot\mathrm{m}^2}{\mathrm{s}^2\cdot\mathrm{A}^2} = \frac{\mathrm{kg}\cdot\mathrm{m}^2}{\mathrm{C}^2} = \frac{\mathrm{J}}{\mathrm{A}^2} = \frac{\mathrm{T}\cdot\mathrm{m}^2}{\mathrm{A}} = \frac{\mathrm{Wb}}{\mathrm{A}} = \frac{\mathrm{V}\cdot\mathrm{s}}{\mathrm{A}} = \frac{\mathrm{s}^2}{\mathrm{F}} = \frac{1}{\mathrm{F}\cdot\mathrm{Hz}^2} = \Omega\cdot\mathrm{s}$$

electromagnetism – some remarks to Maxwell’s equations

Maxwell's equations are a set of 4 partial differential equations that, together with the Lorentz force law, form the foundation of classical electrodynamics, classical optics, and electric circuits.

In the framework of this lecture, few laws build a part of the Maxwell’s equation system (Gauss’s law for magnetism, Ampere's circuital law and Faraday's law of induction),
But the formalism of Maxwell's equations will be the topic of next term – you can look forward to it! ;-)

Maxwell's equations

Name	Integral equations	Differential equations
Gauss's law	$\oiint_{\partial\Omega} \mathbf{E}\cdot \mathrm{d}\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_{\Omega} \rho\,\mathrm{d}V$	$\nabla\cdot\mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's law for magnetism	$\oiint_{\partial\Omega} \mathbf{B}\cdot \mathrm{d}\mathbf{S} = 0$	$\nabla\cdot\mathbf{B} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\oint_{\partial\Sigma} \mathbf{E}\cdot \mathrm{d}\boldsymbol{\ell} = -\frac{\mathrm{d}}{\mathrm{d}t}\iint_{\Sigma} \mathbf{B}\cdot \mathrm{d}\mathbf{S}$	$\nabla\times\mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
Ampère's circuital law (with Maxwell's addition)	$\oint_{\partial\Sigma} \mathbf{B}\cdot \mathrm{d}\boldsymbol{\ell} = \mu_0\iint_{\Sigma} \mathbf{J}\cdot \mathrm{d}\mathbf{S} + \mu_0\varepsilon_0\frac{\mathrm{d}}{\mathrm{d}t}\iint_{\Sigma} \mathbf{E}\cdot \mathrm{d}\mathbf{S}$	$\nabla\times\mathbf{B} = \mu_0\left(\mathbf{J} + \varepsilon_0\frac{\partial \mathbf{E}}{\partial t}\right)$