Lecture 6: magnetism, electromagnetism

Content:

- introduction, magnetic dipole
- basic quantities in magnetism
- magnetic intensity and induction
- magnetic permeabilty,
- diamagnetic, paramagnetic and ferromagnetic material
- magnetic flux
- laws of electromagnetic interaction:

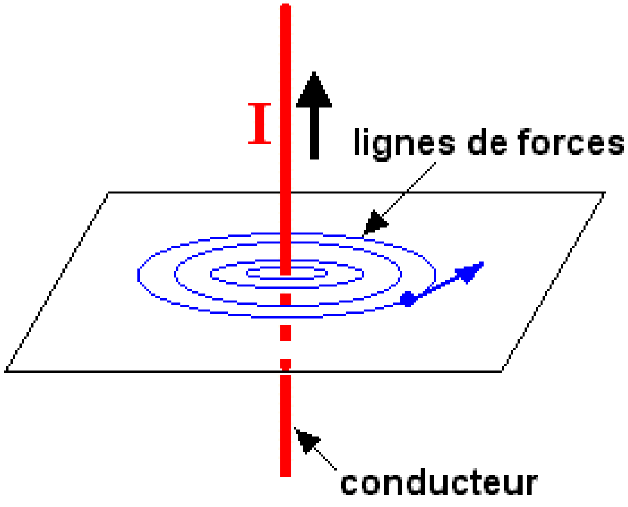
a. Lorentz force (law)
b. Biot-Savart law
c. Amper’s law
d. Faraday’s law of induction

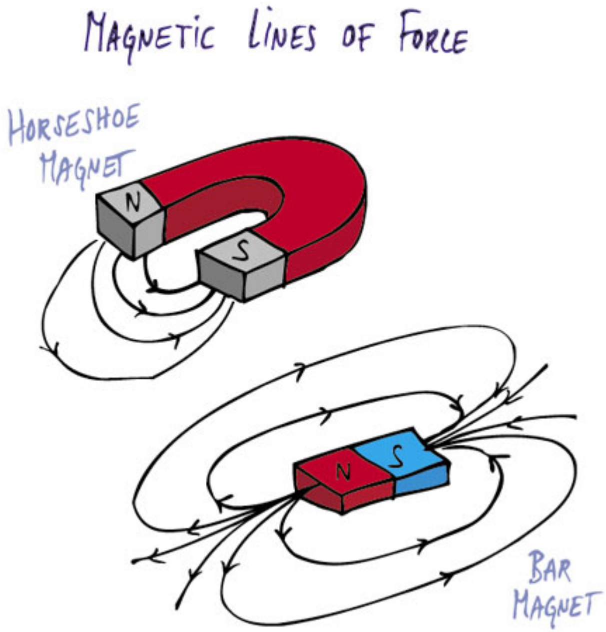
- comments to units

magnetism

A magnetic field is the effect of magnetic materials and electric currents. On the macroscopic level it is presented by force interaction. The magnetic field at any given point is specified by both a direction and a magnitude (or strength); as such it is a vector field.

Electric and magnetic fields are very close related – therefore we speak about electro-magnetic interaction or more simply about electromagnetism (EM).

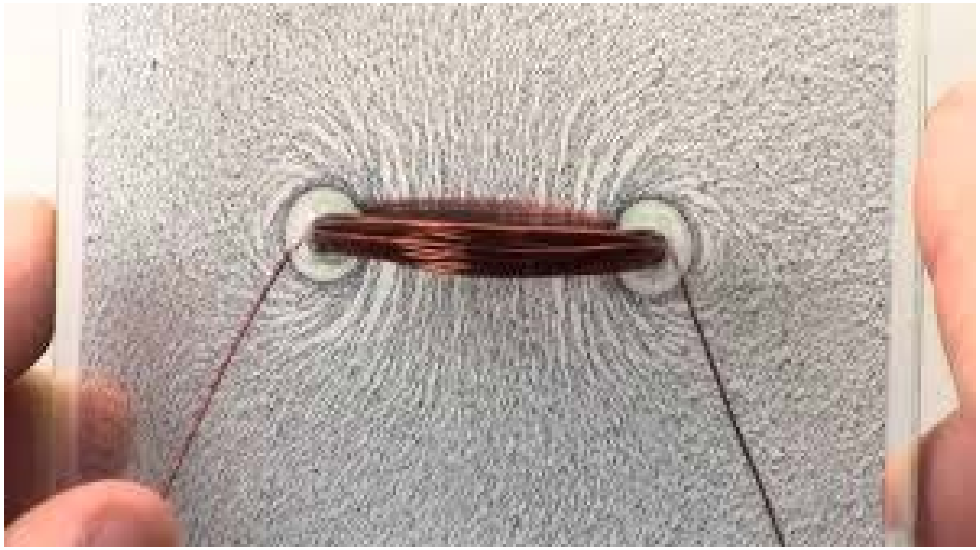




<u>Comment:</u> Also the magnetic field of a permanent magnet is caused by the movement of electric charges (inside of the atomic structure of the material).

magnetism

The magnetic field is often represented by magnetic field lines, which show the direction of the field at different points.

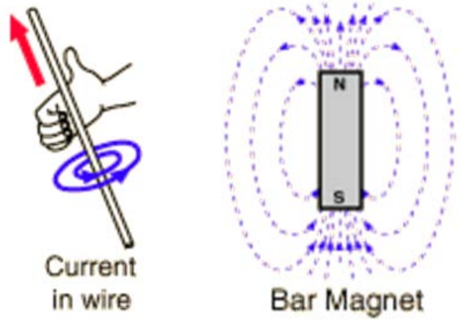
 

experiment - iron fillings around a bar magnet:
https://www.youtube.com/watch?v=8llkHQtaOlg

experiment - iron fillings around a wire:
https://www.youtube.com/watch?v=opJYLFvI-RE

magnetism - introduction

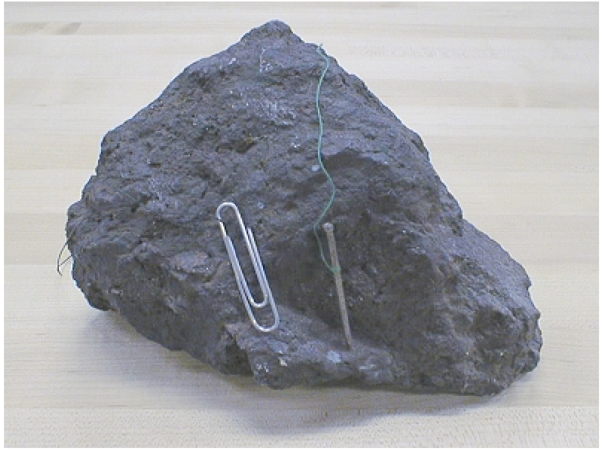
Magnetism, phenomenon associated with the motion of electric charges. This motion can take many forms.
It can be an electric current in a conductor or charged particles moving through space, or it can be the motion of an electron in atomic orbit (Encyclopaedia Britannica).



electric current $\rightarrow$ electromagnets

motion of an electron in atomic orbit $\rightarrow$ permanent (bar) magnets

Permanent magnets are build from ferromagnetic materials such as iron (Fe), cobalt (Co), nickel (Ni) or gadolinium (Gd).
Bar magnets attract or repel other magnets.
These 4 elements have so called ferromagnetic properties, which we will touch later on.



lodestone

Magnetic field has exclusively a dipole character !!!

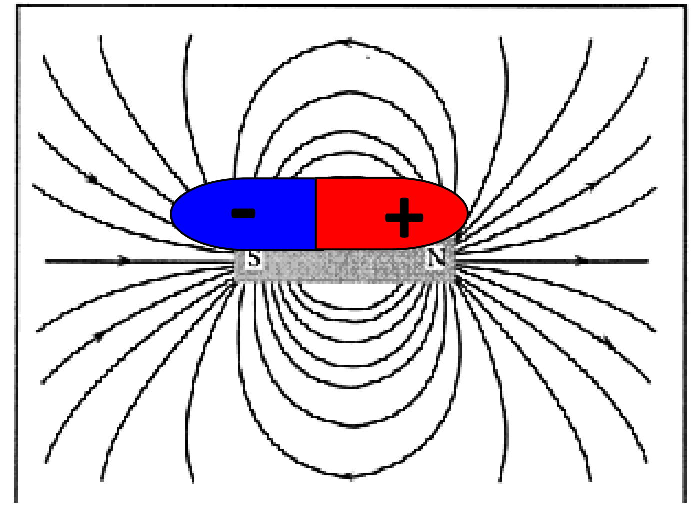
Recall that an electric dipole consists of two equal but opposite charges separated by some distance, such as in a polar molecule. Every bar magnet or an electormagnet is a magnetic dipole.

Note how the ***E*** field due an electric dipole is just like the magnetic field (***B*** field) of a bar magnet. Field lines emanate from the **+** or N pole and re-enter the **-** or S pole.

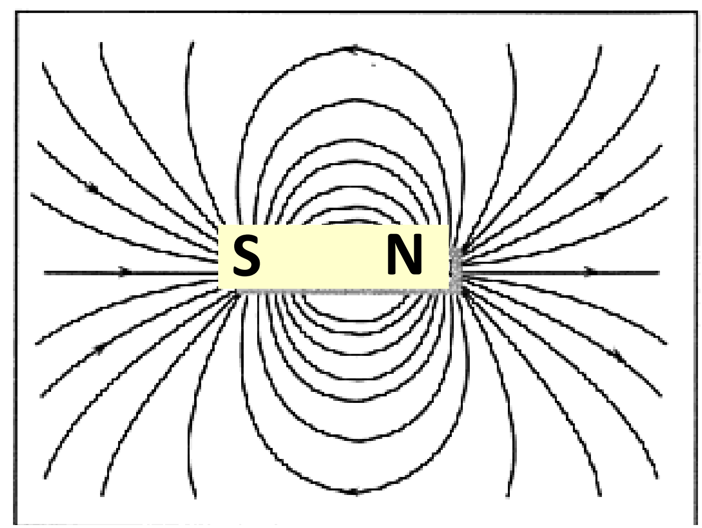
Although they look the same, they are different kinds of fields. ***E*** fields affect any charge in the vicinity, but a ***B*** field only affects moving charges. As with charges, opposite poles attract and like poles repel.

Magnetic dipole moment – important parameter (will be explained later).

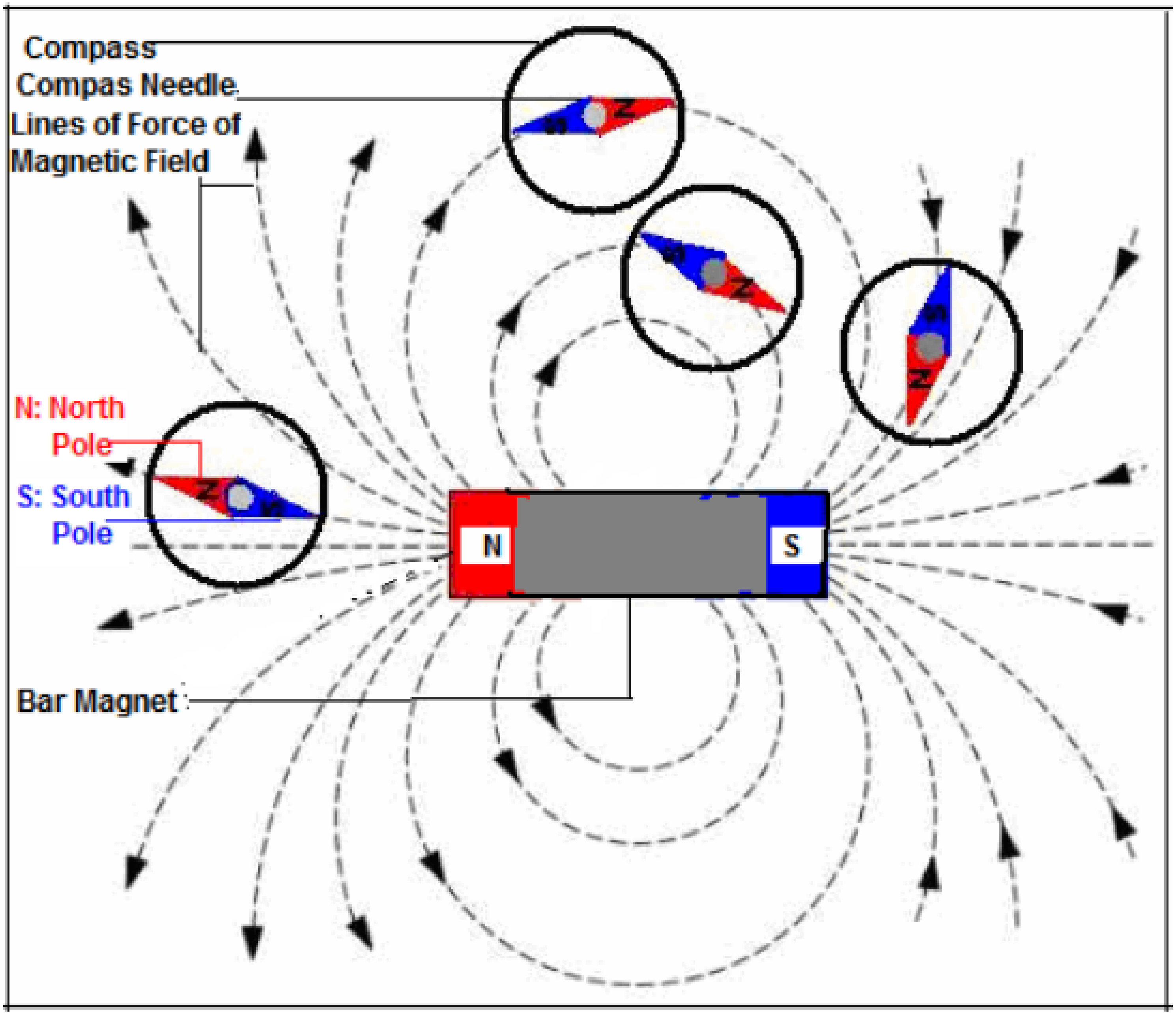
B is the field of magnetic induction (will be explained later on).



electric dipole and ***E*** field

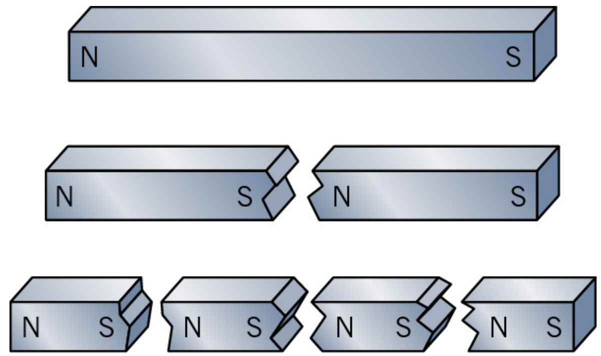


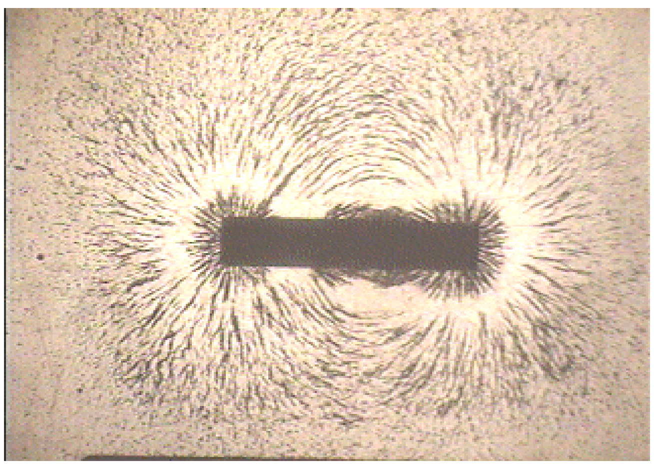
magnetic dipole and ***B*** field

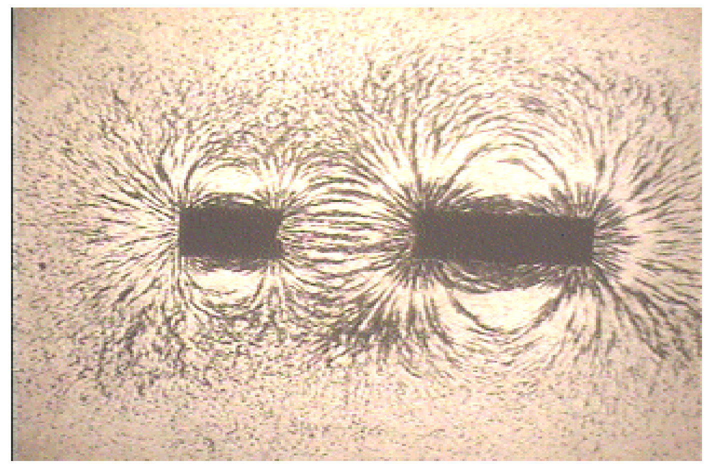


Field lines emanate from the **+** or N pole and reenter the **-** or S pole.

magnetism - introduction





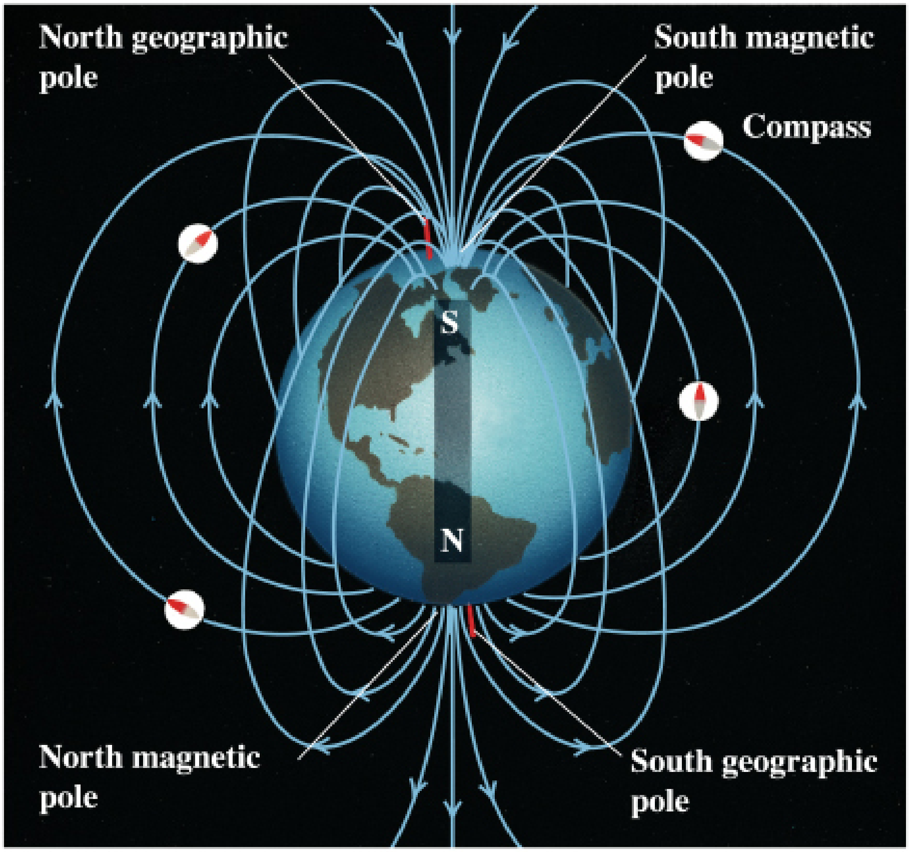


Magnetic monopoles do not exist (!), meaning it is impossible to isolate a N or S pole. When we try to separate the two poles by breaking the magnet, we only succeed in producing two distinct dipoles.

Some particle theories predict their existence, but there is no experimental evidence that they exist.

magnetism - introduction

Earth magnetic field is generated by the effect of movement of conductive masses in the outer Earth core – so called hydromagnetodynamic effects.



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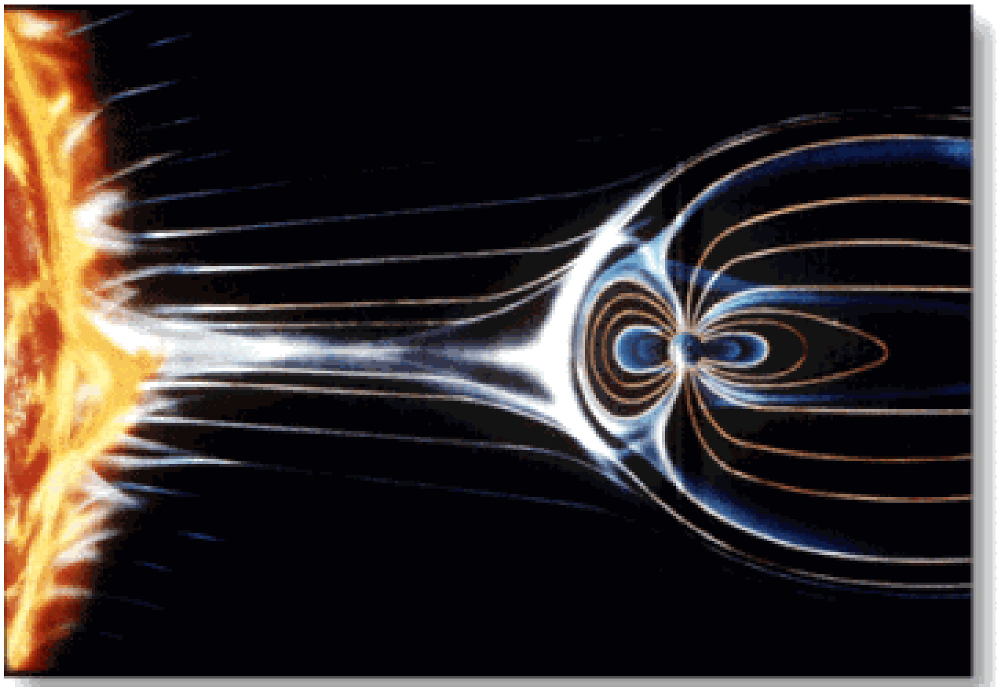
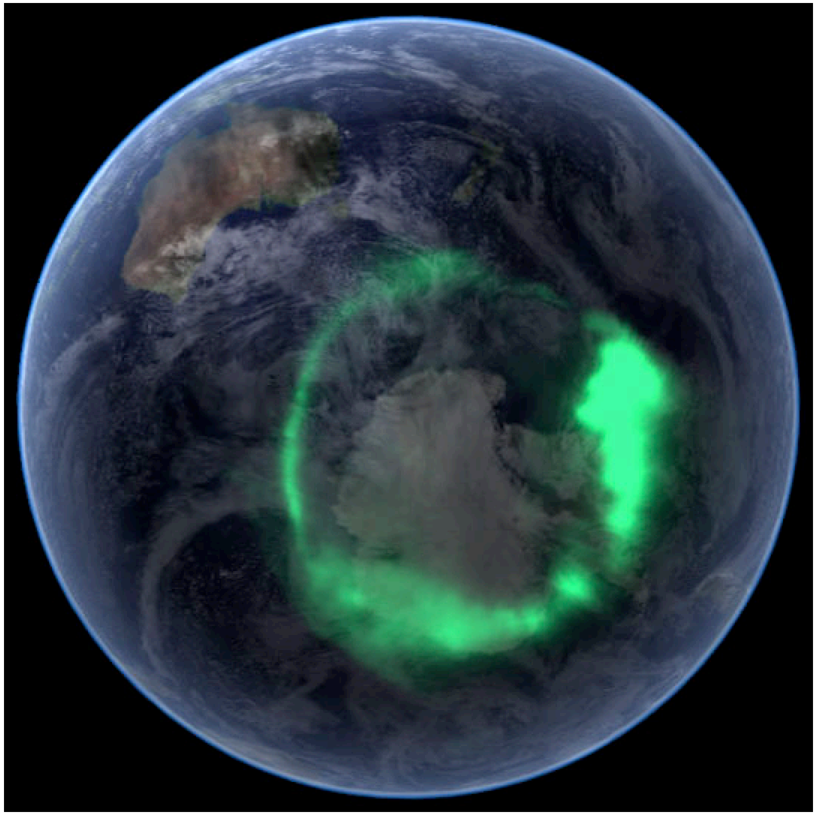
magnetism - introduction

Thanks to the Earth magnetic field the life conditions are acceptable on the Earth – magnetic field (called also magnetosphere) build “a shield”, which protects Earth before so called solar wind (stream of high-energy particles emanated from the Sun).





magnetism – basic quantities (intensity vs. induction)

Magnetic field is described by means of two very close vector quantities:

magnetic intensity **H** (unit, [$A \cdot m^{-1}$]) and

magnetic induction **B** (unit, [T] = tesla);

Relation between them is given by this simple equation:

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

where μ – magnetic permeability, (unit: [$H \cdot m^{-1} = N \cdot A^{-2}$]),
it describes the ability of a material to be magnetized by the action of an outer magnetic field.

We use often so called relative magnetic permeability:

$$\mu_r = \mu/\mu_0 \;\Rightarrow\; \mu = \mu_r \cdot \mu_0$$

μ_0 – permeability of vacuum (free space) or
magnetic constant ($4\pi \cdot 10^{-7}\ H \cdot m^{-1}$).

<u>Comment:</u> Units tesla and henry will be explained later on.

magnetism – basic quantities (intensity vs. induction)

Magnetic intensity **H** ($[A \cdot m^{-1}]$).
Describes the measure of force effects (magnetisation effects) of the magentic field. In comparison with magnetic induction, it does not include the reaction of the material to the outer magnetic field.

Magnetic induction **B** ([T]).
Characterizes force effect of the magnetic field on a moving charge or a conductor with electric current, it does include the reaction of the material to the outer magnetic field (its magnetisation or "resistance" to it).

The best way to understand **H** vs. **B** is the so called hysteresis (we will come to it in a moment).

Alternative names for *B* and *H*

B	
name	**used by**
magnetic flux density	electrical engineers
magnetic induction	electrical engineers
magnetic field	physicists
H	
name	**used by**
magnetic field intensity	electrical engineers
magnetic field strength	electrical engineers
auxiliary magnetic field	physicists
magnetizing field	physicists

magnetism – basic quantities (permeability)

Based on the value μ_r ($\mu_r=\mu/\mu_0$) we can divide materials to:

diamagnetic ($\mu_r < 1$), they weaken the magnetic field, they are repelled by the outer magnetic field (form an opposite induced field)

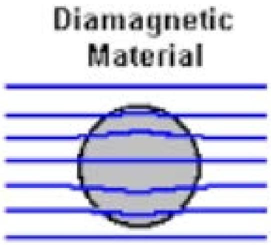
(e.g.: water, organic substance, but also some metals: Cu, Ag, Au, Hg, Bi,)

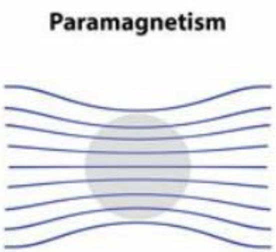
paramagnetic ($\mu_r > 1$), slightly amplify the magnetic field, they are attracted by the outer magnetic field (form a field in the direction of the outer field), but do not remember this magnetisation

(most of chemical elements, e.g.: Al, Mn, Cr, Pt)

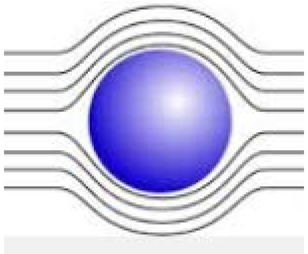
ferromagnetic ($\mu_r >>1$) strongly amplify the magnetic field, they are attracted by the outer magnetic field (form a field in the direction of the outer field), but do remember this magnetisation (4 metals: Fe, Ni, Co, Gd).

Comment: Strongest diamagnetic behaviour show superconductors, which can almost fully prohibit the entering of the outer magnetic field into their volume (beside a thin surface layer), so for their centre is valid $\mu_r = 0$.

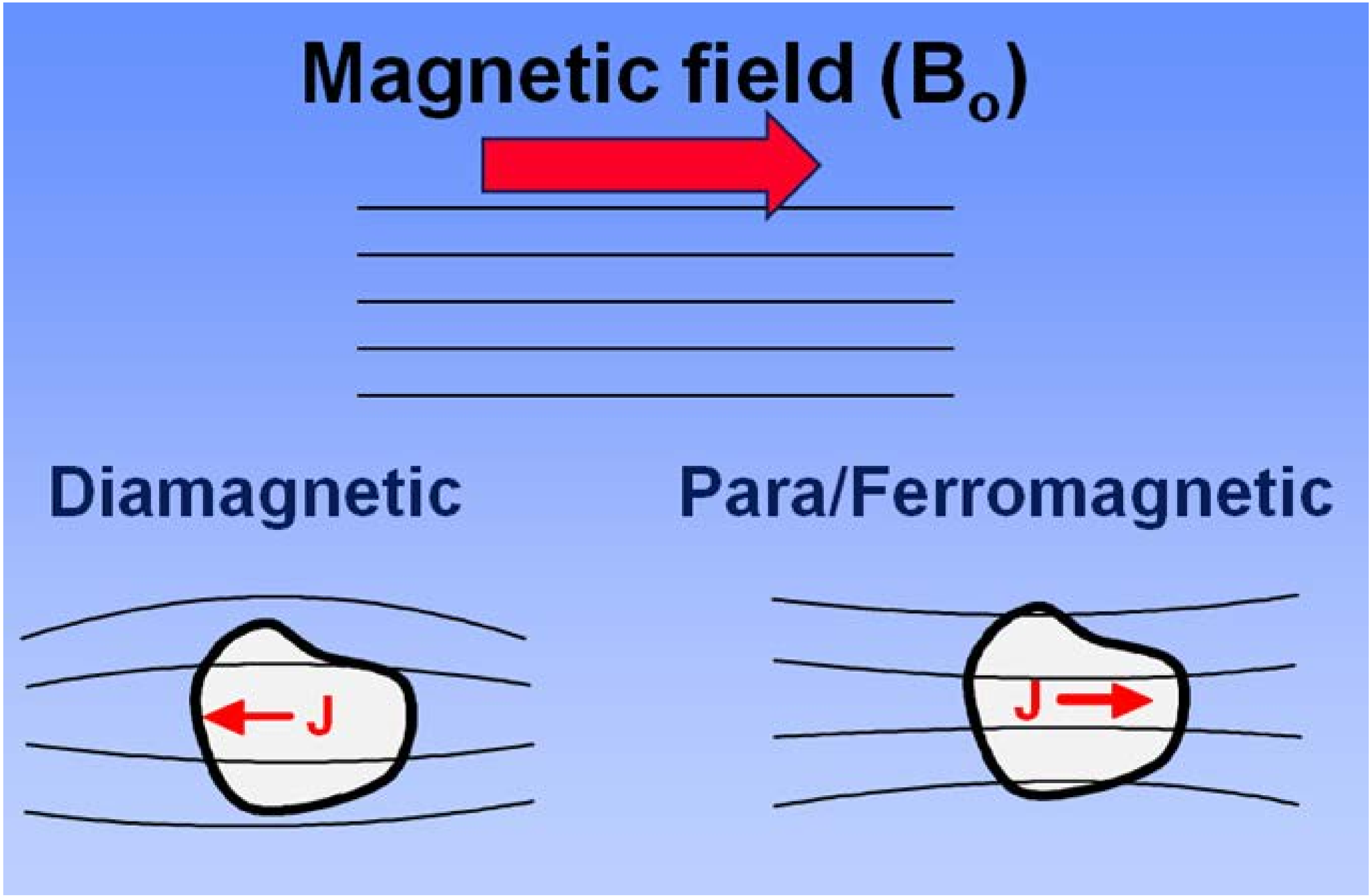




superconductor:



magnetism – basic quantities (permeability)



J is sometimes named as magnetisation vector diamagnetic ($\mu_r < 1$), paramagnetic ($\mu_r > 1$) , ferromagnetic ($\mu_r >> 1$)

Material	Type	Relative permeability
Bismuth	Diamagnetic	0.99983
Silver	Diamagnetic	0.99998
Copper	Diamagnetic	0.999991
Lead	Diamagnetic	0.999983
Water	Diamagnetic	0.999991
Vacuum	Nonmagnetic	1
Air	Paramagnetic	1.0000004
Aluminum	Paramagnetic	1.00002
Palladium	Ferromagnetic	1.0008
Cobalt	Ferromagnetic	250
Nickel	Ferromagnetic	600
Mild Steel (0.2 C)	Ferromagnetic	2,000
Iron (0.2 impurity)	Ferromagnetic	5,000
Silicon Iron	Ferromagnetic	7,000
Mumetal	Ferromagnetic	100,000
Purified iron (0.05 impurity)	Ferromagnetic	200,000
Supermalloy	Ferromagnetic	1,000,000

magnetism – basic quantities (susceptibility)

Some scientific branches work more with magnetic susceptibility (than permeability):

$$\mu_r = 1 + \chi$$

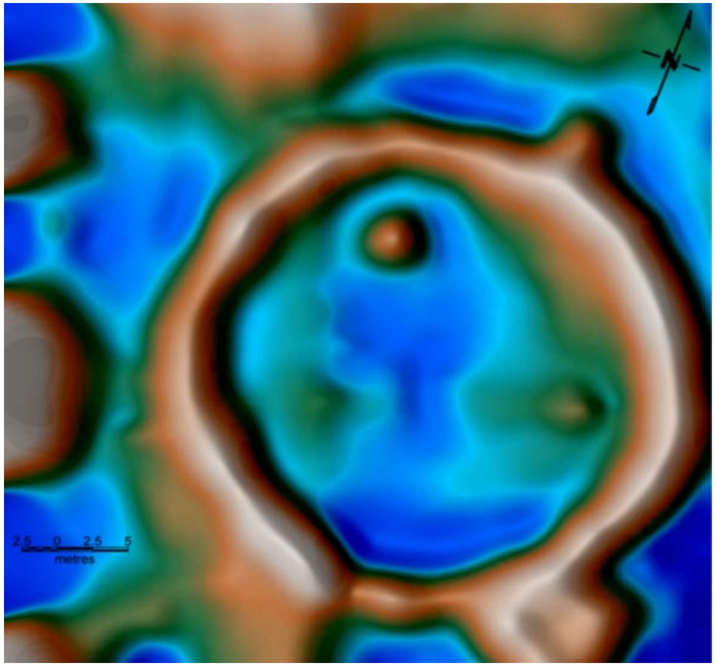
diamagnetic ($\chi < 0$),
paramagnetic ($\chi > 1$),
ferromagnetic ($\chi >> 1$)

Comment: Some ferromagnetic minerals in a colloidal form are products of the metabolism of some humus bacteria, when rests of plants are transformed into humus.

utilization of magnetic properties of humus layers in archaeology

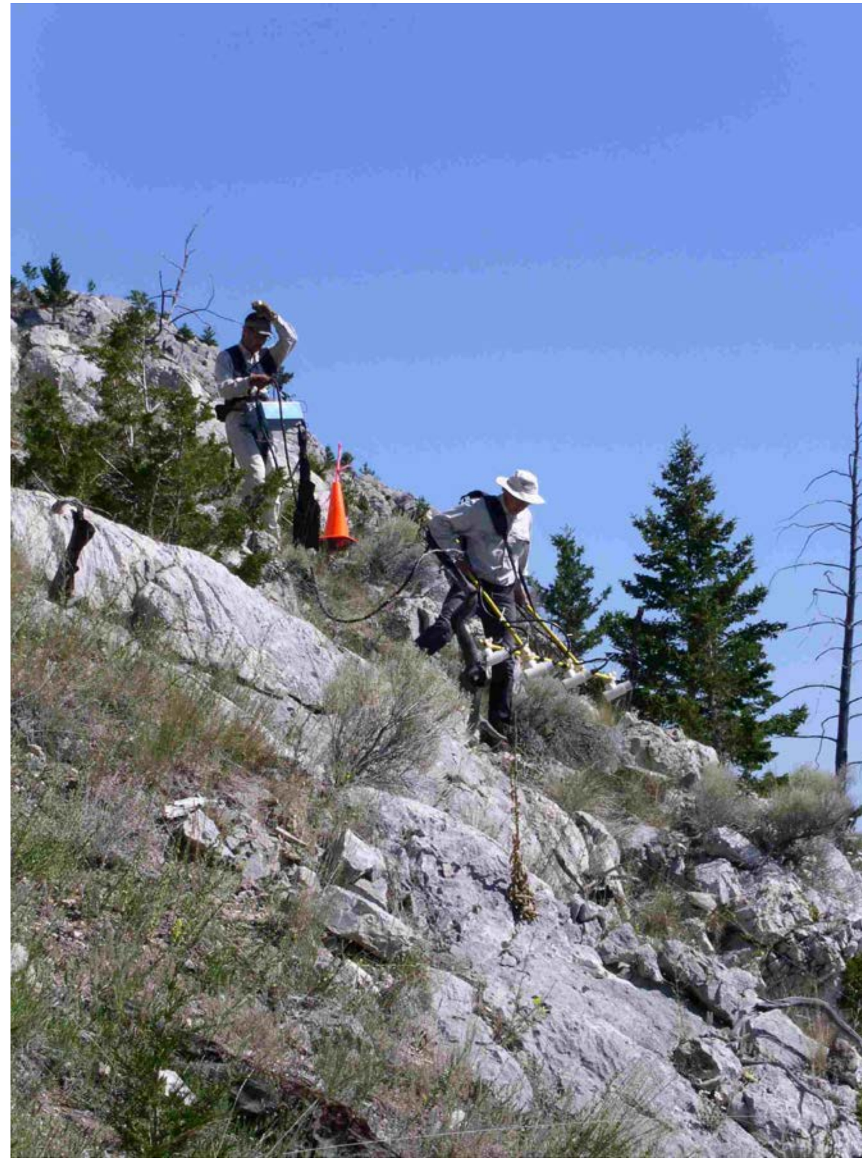
areal photography

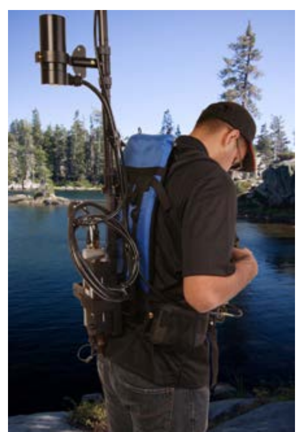
measured magnetic field



site BRANČ, close to Nitra, 18. cent. BC

utilization of magnetic properties of humus layers in archaeology

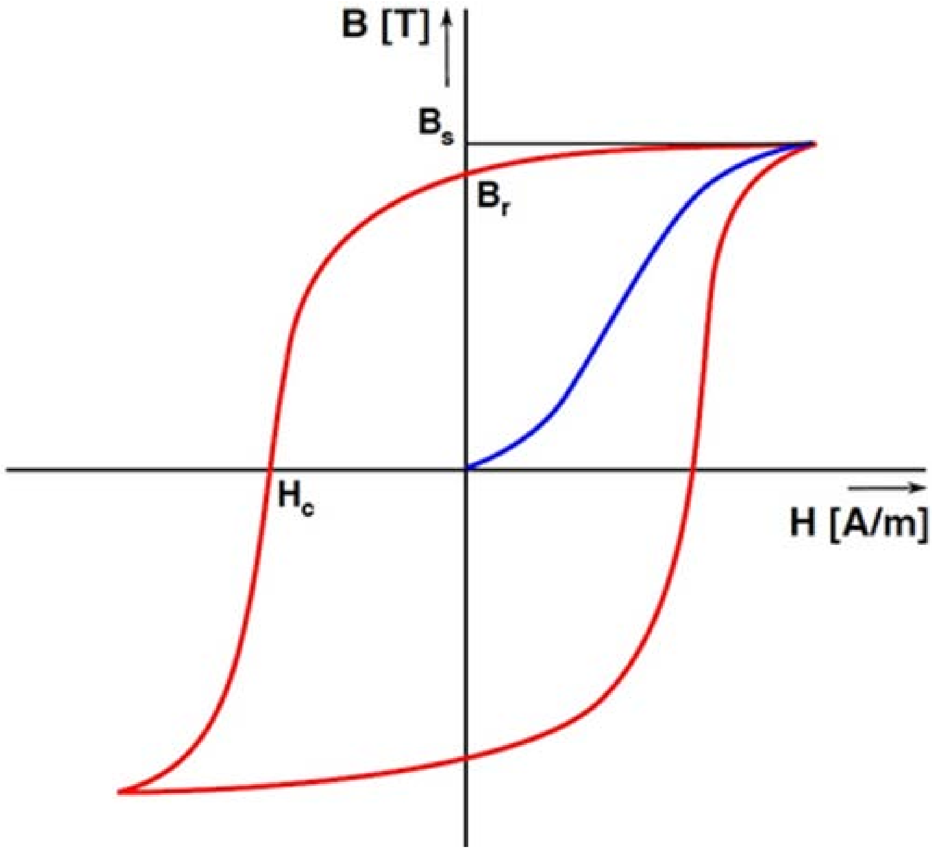




different instruments for outdoor magnetic field measurement

magnetism – basic properties (hysteresis)

Ferromagnetic materials „can hold“ magnetisation also after „switching off“ the outer magnetising field. This is connected with the so called magnetic hysteresis – often displayed in a form of a hysteresis curve (a **H**-**B** graph):



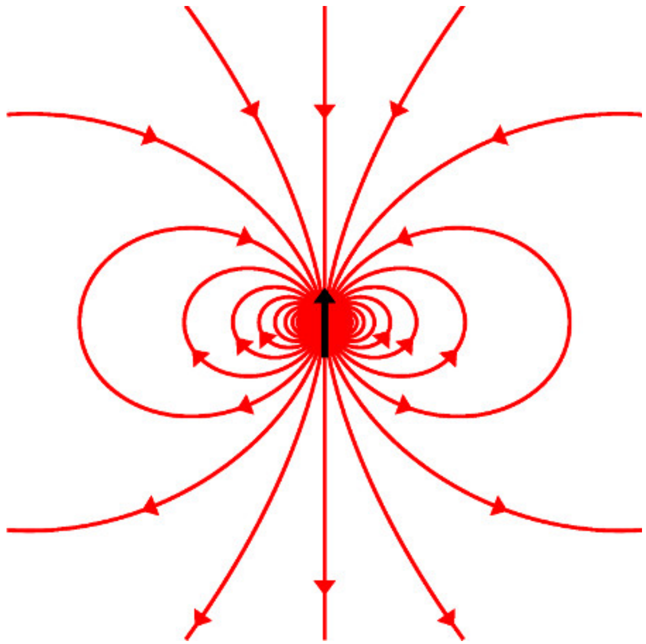
B$_S$ – saturation stage (max. value of **B**),
B$_r$ – remanent magnetisation,
H$_C$ – coercitivity intensity,

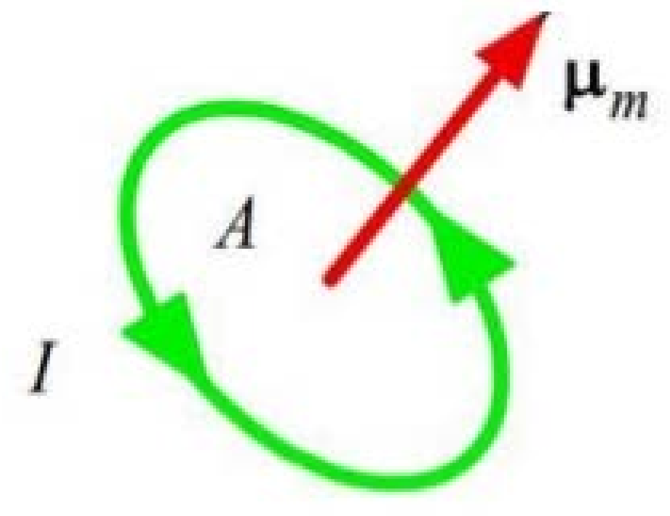
Based on the **H**$_C$ value we dived ferromagnetic materials to soft (small **H**$_C$) and hard (large **H**$_C$).

To demagnetize the remanent magnetisation requires heat or a magnetic field in the opposite direction.
This is the effect that provides the element of memory in a hard disk drive.

magnetism – basic quantities (magnetic moment)

Magnetic moment **μ** is connected with a torque acting on a dipole by means of the magnetic field **B**,
unit: N·m/T = A·m^2 = J/T .

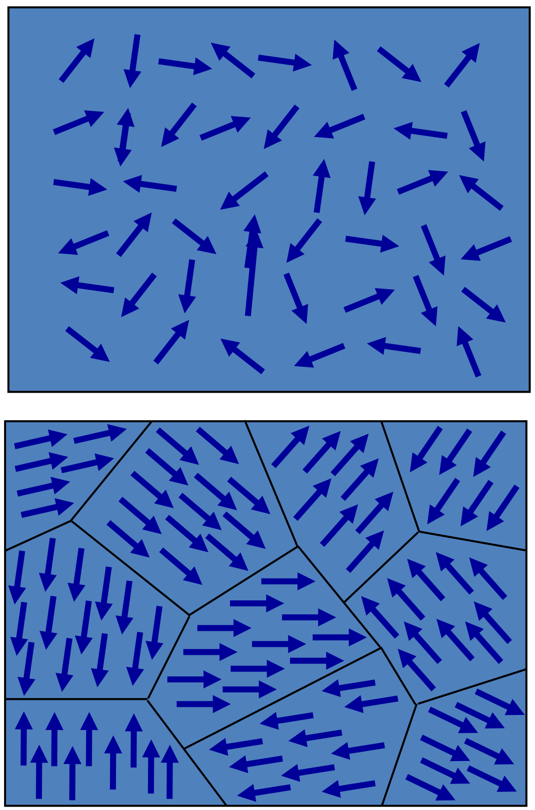




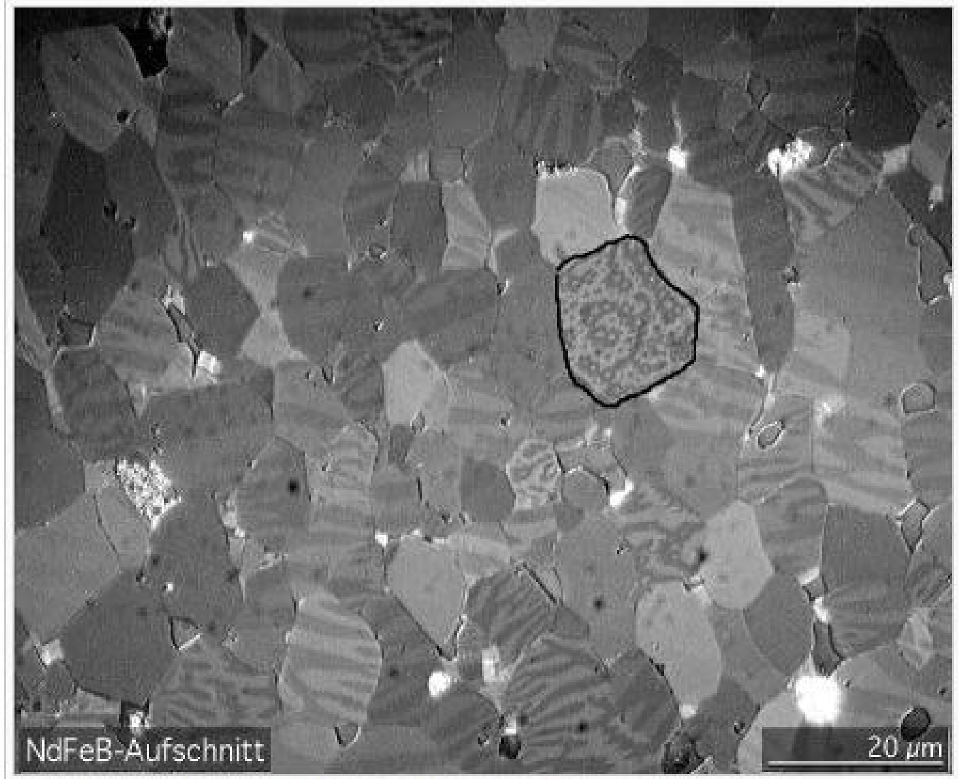
In atomic physics we recognize the electron magnetic moment:
$-9284.764 \cdot 10^{-27}$ J/T .

magnetism – basic properties (magnetic domains)

Electrones build with their movement a local (elementary) magnetic dipole moment of an atom. These magnetic moments can be cancelled (paramagnetic) or amplified (ferromagnetic), when they are self-organized in special zones, so called magnetic domains.



schematic visualisation
of magnetic domains

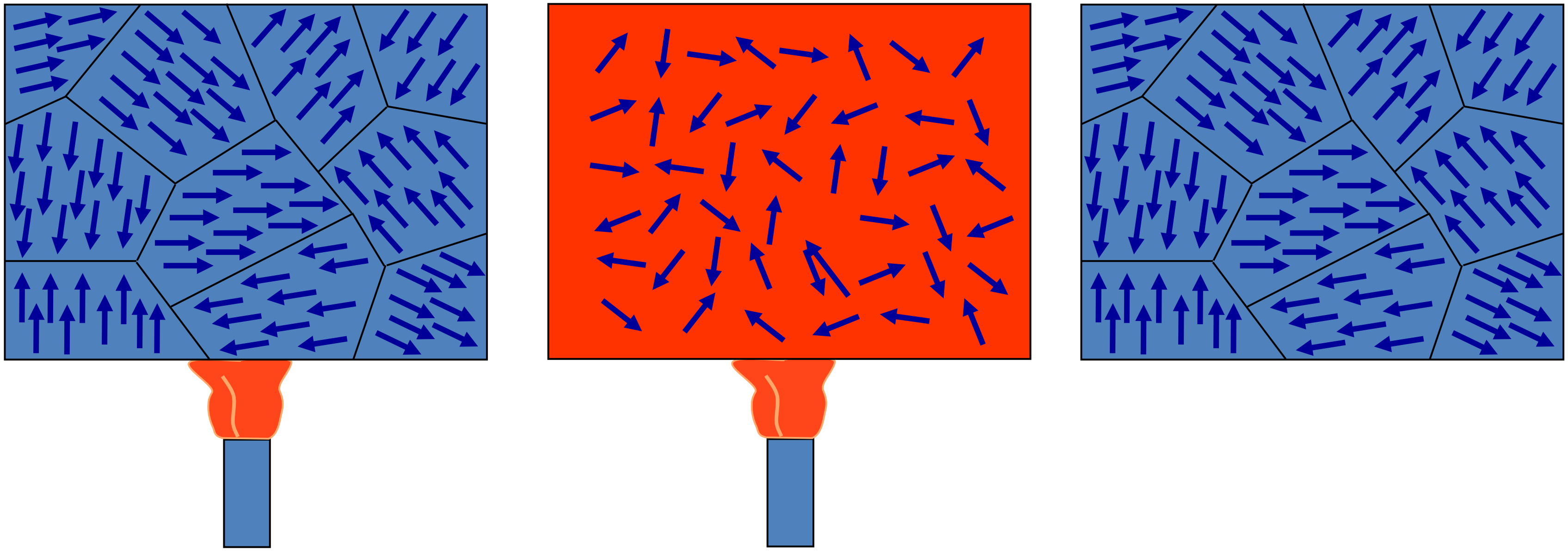


Microcrystalline grains within a piece of NdFeB (the alloy used in neodymium magnets) with magnetic domains made visible with a Kerr microscope. The domains are the light and dark stripes visible within each grain.

magnetism – basic properties (Curie's temperature)

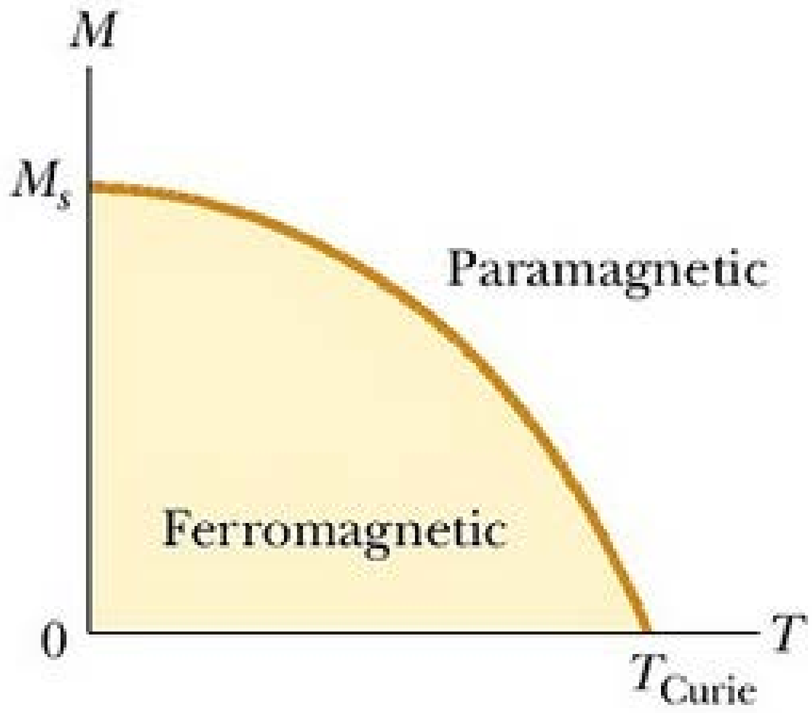
Influence of high temperature (so called Curie's temperature) on remanent magnetisation

When some ferromagnetic material is heated to some temperature (so called **Curie's temperature**), the internal structure of the matter is changed to that of a paramagnetic one. After cooling down, the matter became again ferromagnetic and the structure with magnetic domain is re-established.



magnetism – basic quantities (Curie's temperature)

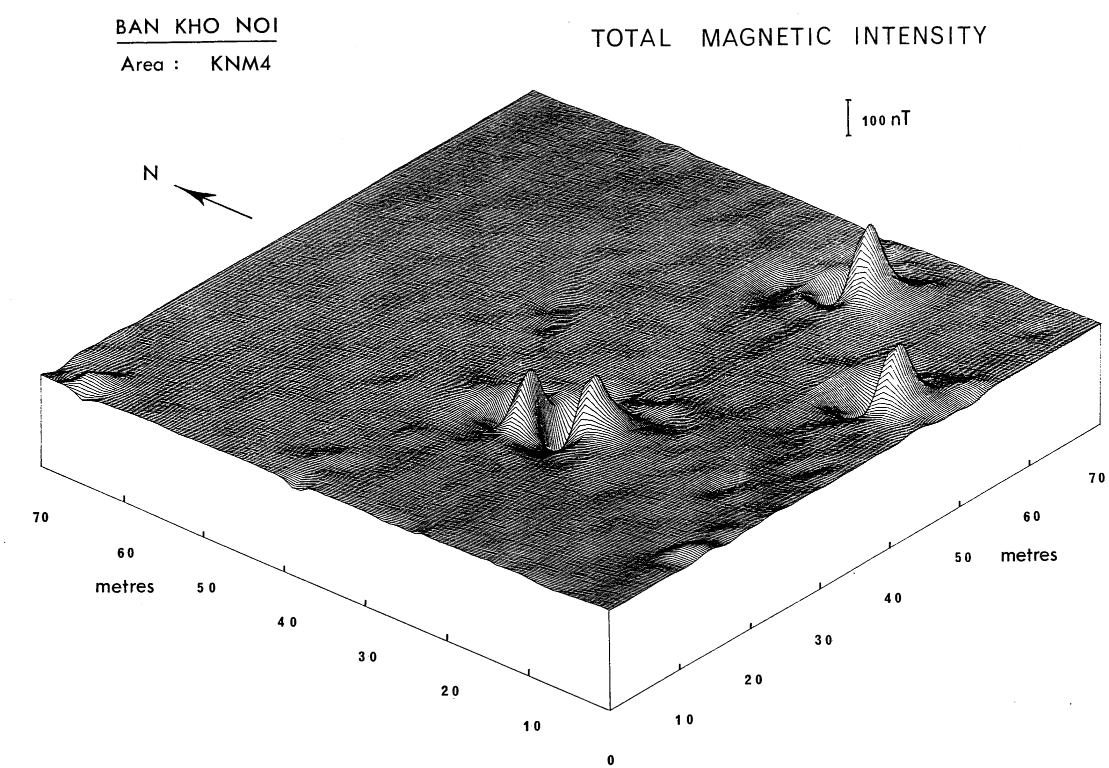
Material	Curie temperature (K)
Iron (Fe)	1043
Cobalt (Co)	1400
Nickel (Ni)	627
Gadolinium (Gd)	292
Dysprosium (Dy)	88
Mn Bi	630
MnSb	587
CrO_2	386
MnAs	318
EuO	69
Iron(III) oxide (Fe_2O_3)	948
Iron(II,III) oxide ($FeOFe_2O_3$)	858



nice simple experiment:
http://sirius.ucsc.edu/demoweb/images/e_m/curie-iron.gif

magnetism – basic quantities (Curie's temperature)

This can be again used in archaeology…



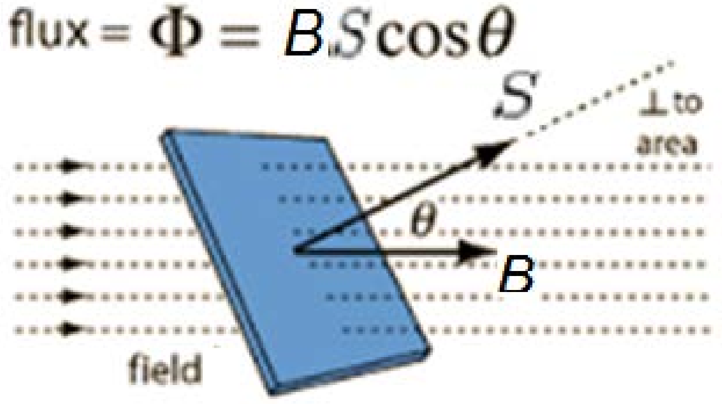
site Ban Kho Noi, Thailand

ceramics kilns
have been excavated

magnetic flux

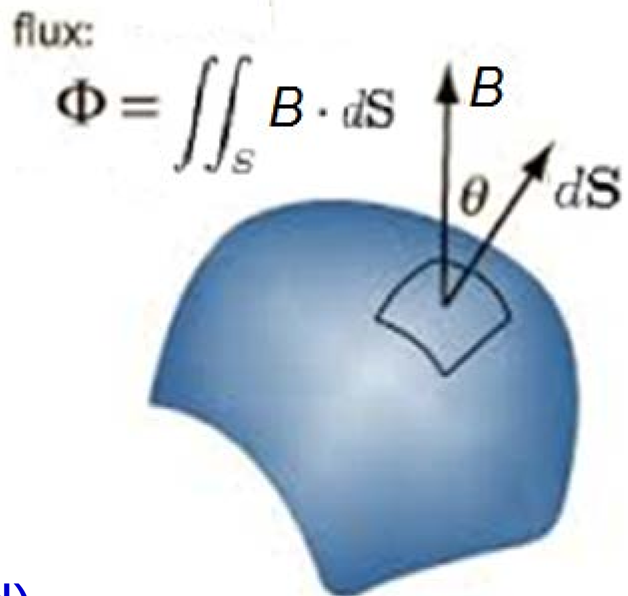
Magnetic flux Φ_B is the measure of flow of the magnetic field **B** through a given area *A*.
Unit: weber, [Wb] = [T·m^2].
For a planar area *A* we can write:

$$\Phi_B = \mathbf{B} \cdot \mathbf{S} = BS\cos\theta,$$



For an irregular area *A* we have to write an integral:

$$\Phi_B = \iint_S \mathbf{B} \cdot d\mathbf{S}.$$



and for closed irregular area *A*:

$$\Phi_B = \oint\!\!\!\oint_S \mathbf{B} \cdot d\mathbf{S} = 0$$

This is so called Gauss's law for magnetism (due to the dipole character of magnetic field).

Lecture 6: magnetism, electromagnetism

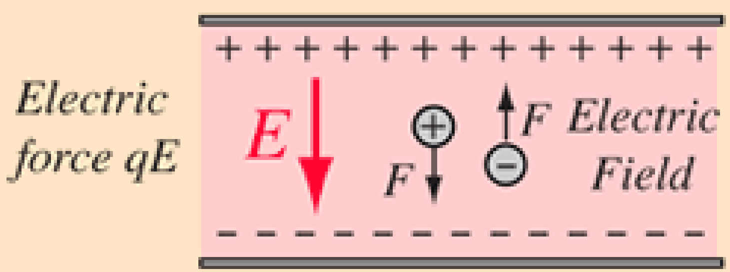
- laws of electromagnetic interaction

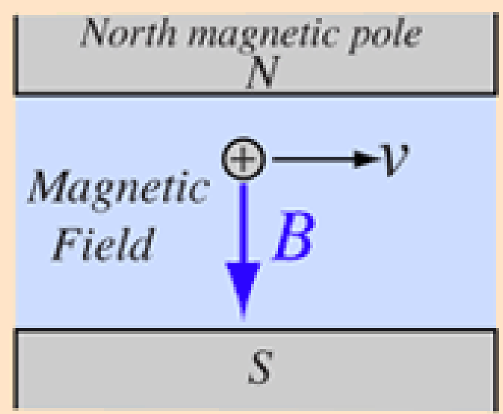
Lorentz force (law)

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

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

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.

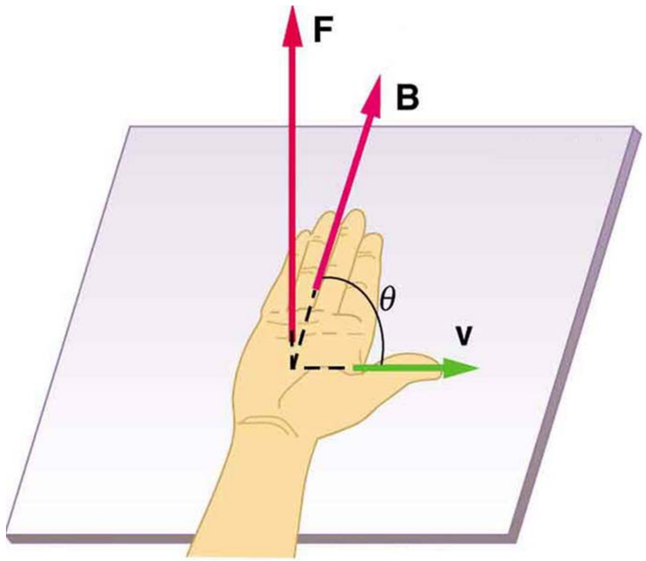




Magnetic force of magnitude $qvB\sin\theta$ perpendicular to both v and B, away from viewer.

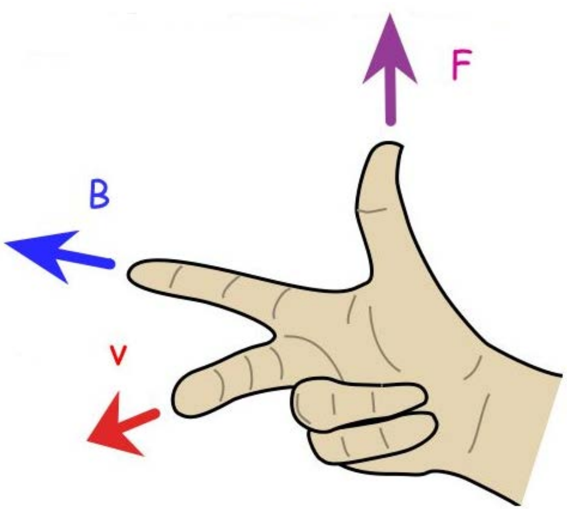
Important: so called right hand rule for the magnetic force.

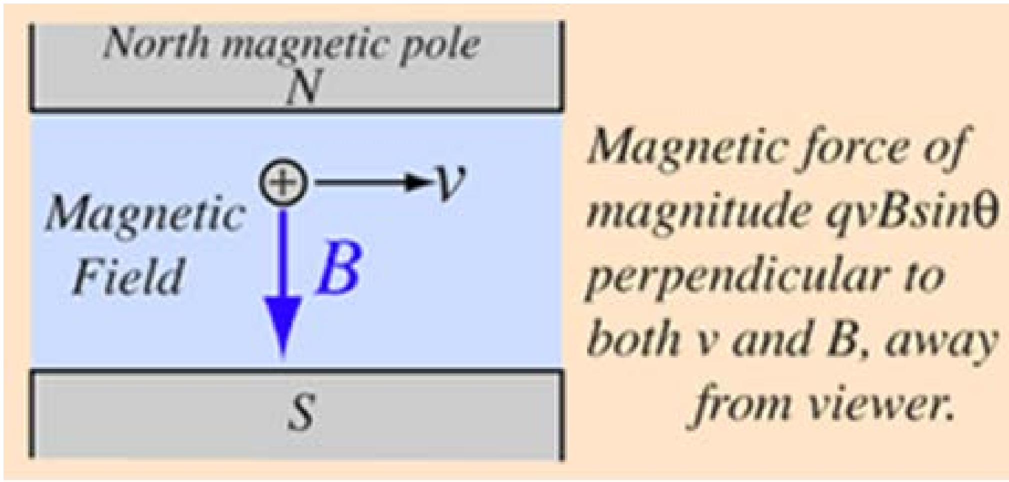
Important: so called right hand rule for the magnetic force.



$F = qvB \sin\theta$

F $\perp$ plane of **v** and **B**



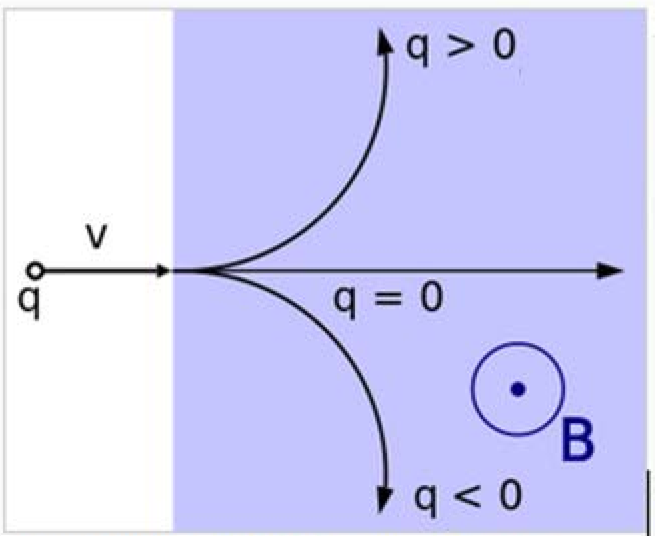


Lorentz force

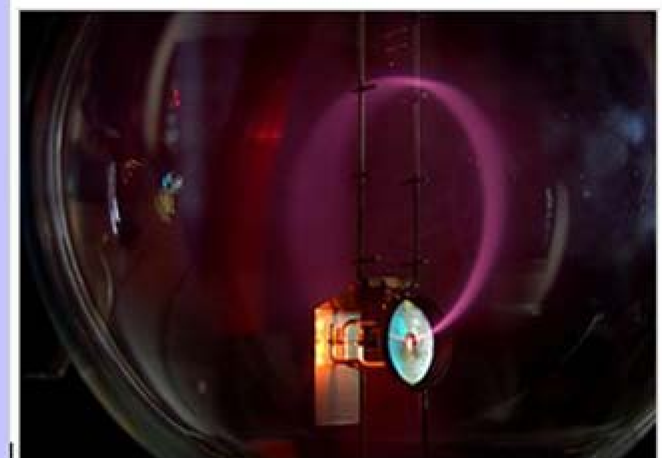
$$\vec{F} = \underbrace{q\vec{E}}_{\text{Electric force}} + \underbrace{q\vec{v}\, x\, \vec{B}}_{\text{Magnetic force}}$$

This is valid not only for a particle with charge *q*, but also on a current-carrying wire in a magnetic field (in the wire the free charges are moving).

Lorentz Force Law (experiment itself starts from approx.1:00 min.): https://www.youtube.com/watch?v=L9zq_fvRuwo



Trajectory of a particle with a positive or negative charge *q* under the influence of a magnetic field *B*, which is directed perpendicularly out of the screen.

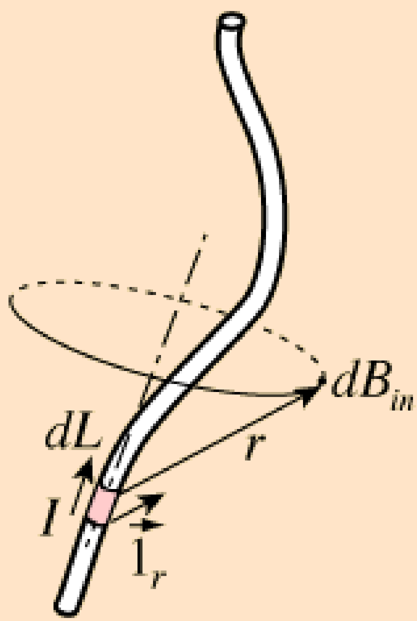


Beam of electrons moving in a circle, due to the presence of a magnetic field. Purple light is emitted along the electron path, due to the electrons colliding with gas molecules in the bulb.

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: $|dB| = C\dfrac{I}{r^2}$



Magnetic field of a current element

$$d\vec{B} = \frac{\mu_0 I d\vec{L} \, x \, \vec{1}_r}{4\pi r^2}$$

where

$d\vec{L}$ = infinitesmal length of conductor carrying electric current I

$\vec{1}_r$ = unit vector to specify the direction of the the vector distance r from the current to the field point.

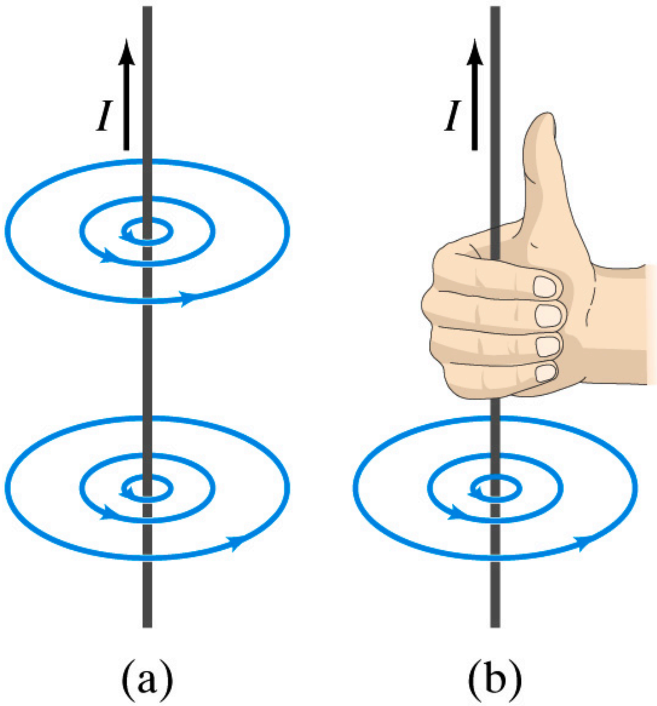
Resulting field **B** we get as a result of integration along the wire.

Biot-Savart law

Result after integration (for a direct wire):

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

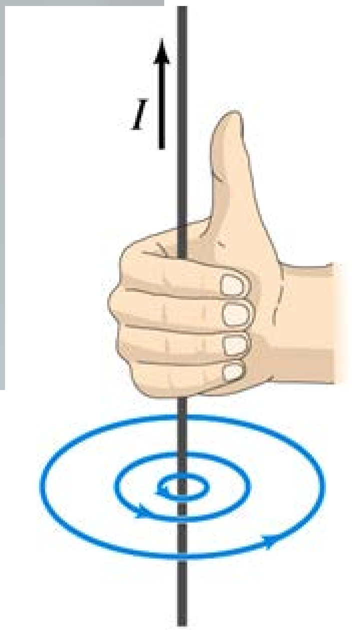
here *r* is the perpendicular distance from a direct wire (with direct current *I*)



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

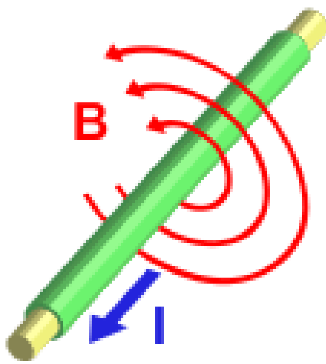
Biot-Savart law

The video from the begin of this lecture:
https://www.youtube.com/watch?v=opJYLFvI-RE



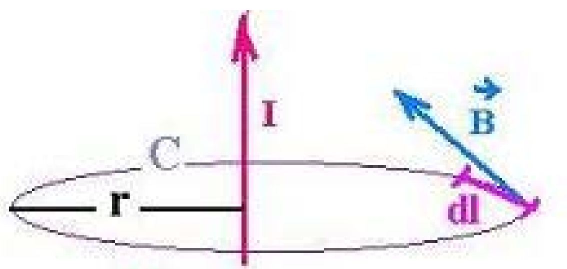
Amper's law (as a consequence of Biot-Savart law)

Also called as Amper's circuital law.



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

Derivation:



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

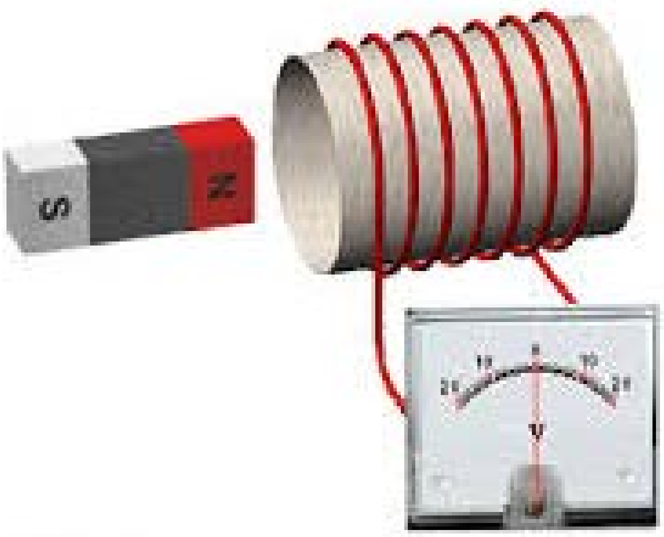
Along a circle the angle between these two vectors (**B** and d**l**) is zero, so it follows:

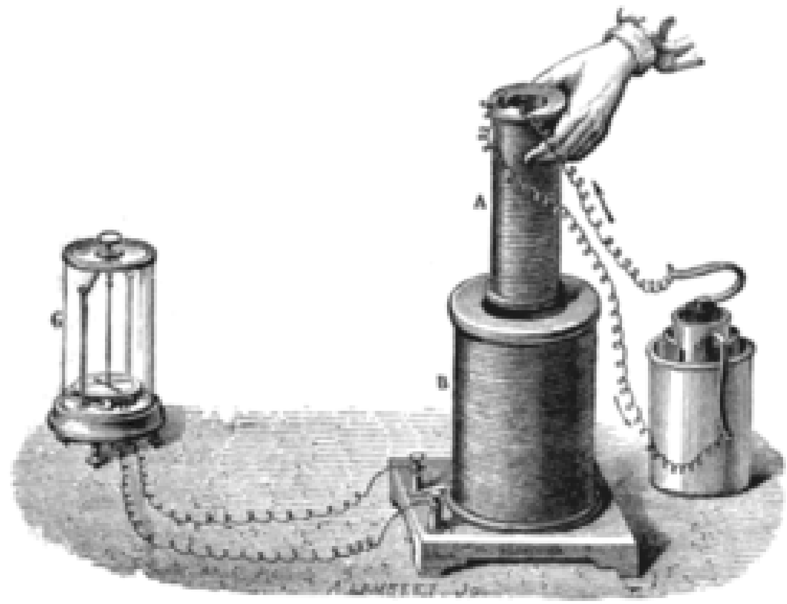
$$\oint_{l(S)} \vec{B}\cdot d\vec{l} = \oint_{l(S)} \left|\vec{B}\right| dl = \left|\vec{B}\right| 2\pi r$$

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.





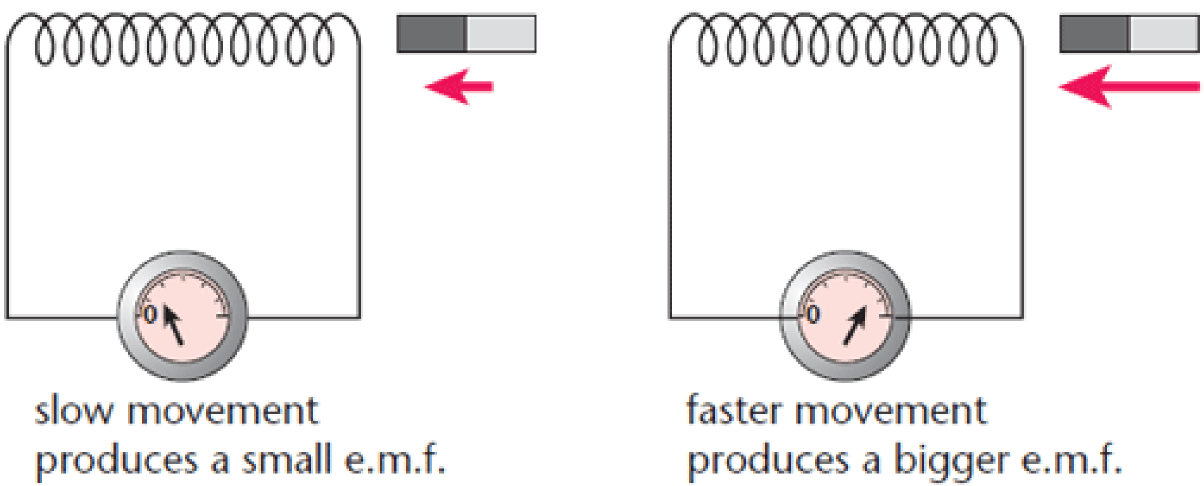
Faraday’s law of induction (experiment):
https://www.youtube.com/watch?v=vwIdZjjd8fo

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:

$$\mathcal{E} = -\frac{d\Phi_B}{dt},$$

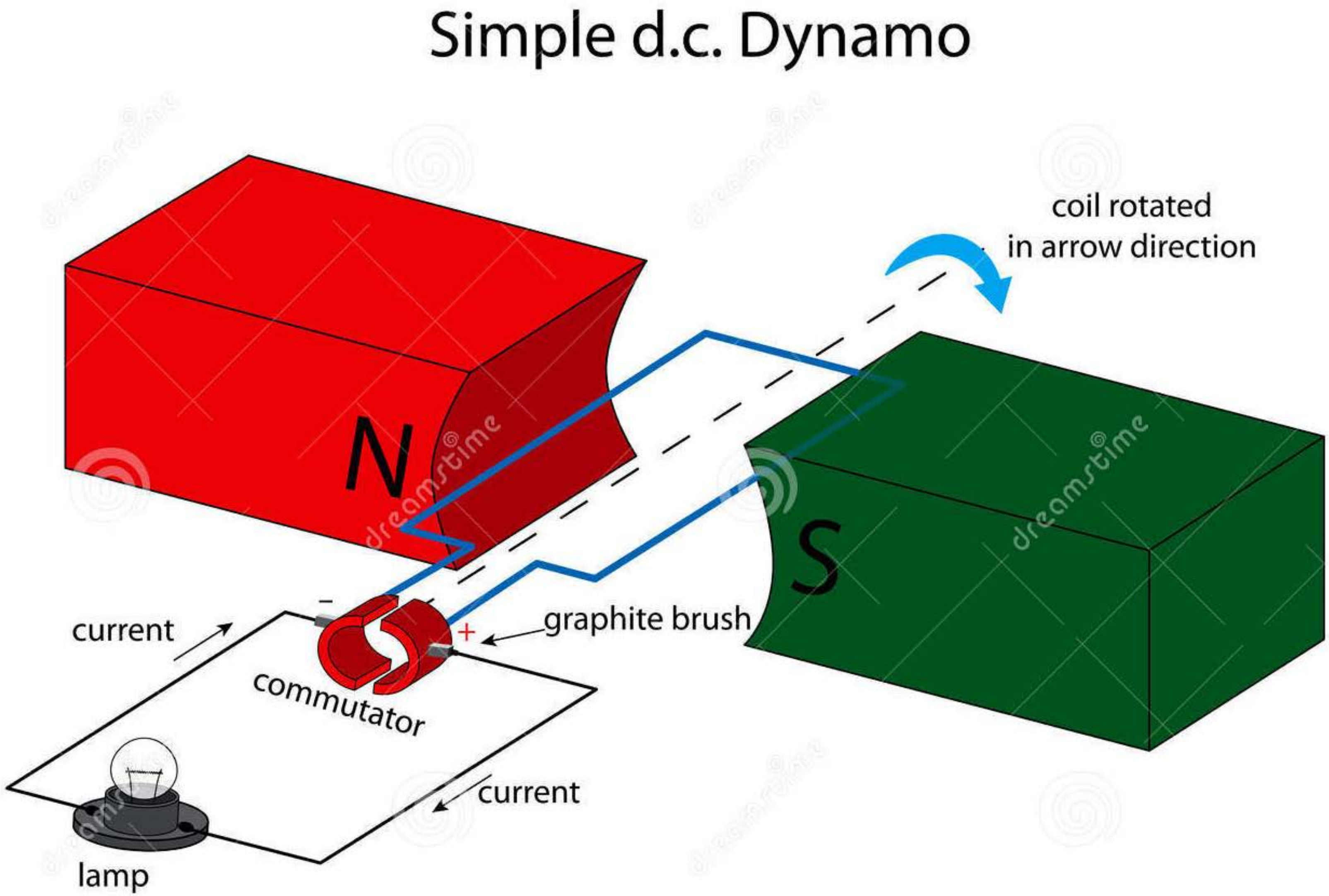
The direction of the electromotive force is given by Lenz's law.



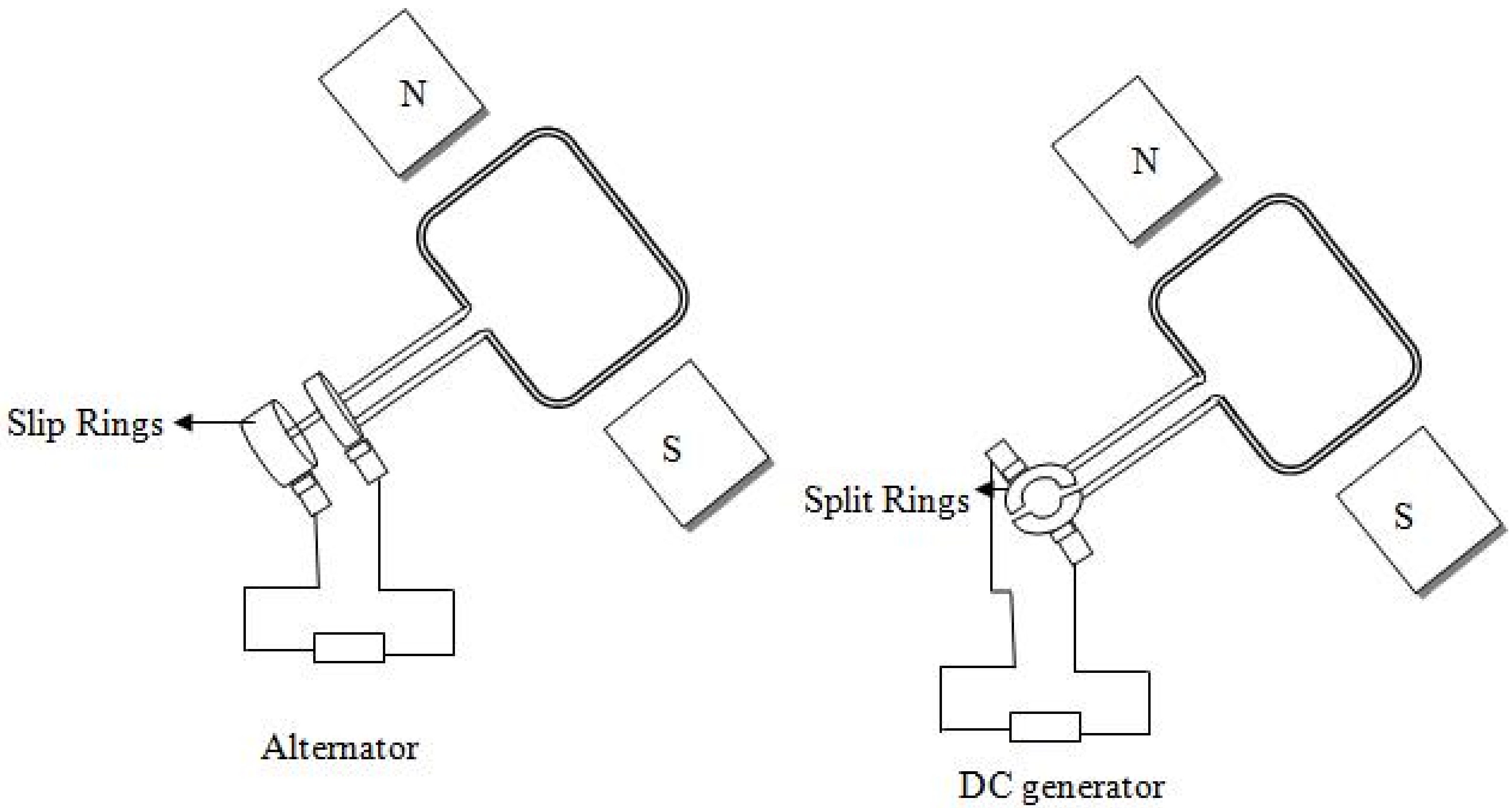
An electromotive force can be originated also in a situation, when a conductor is moving in a magnetic field – principle of a dynamo.

Faraday’s law of induction

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



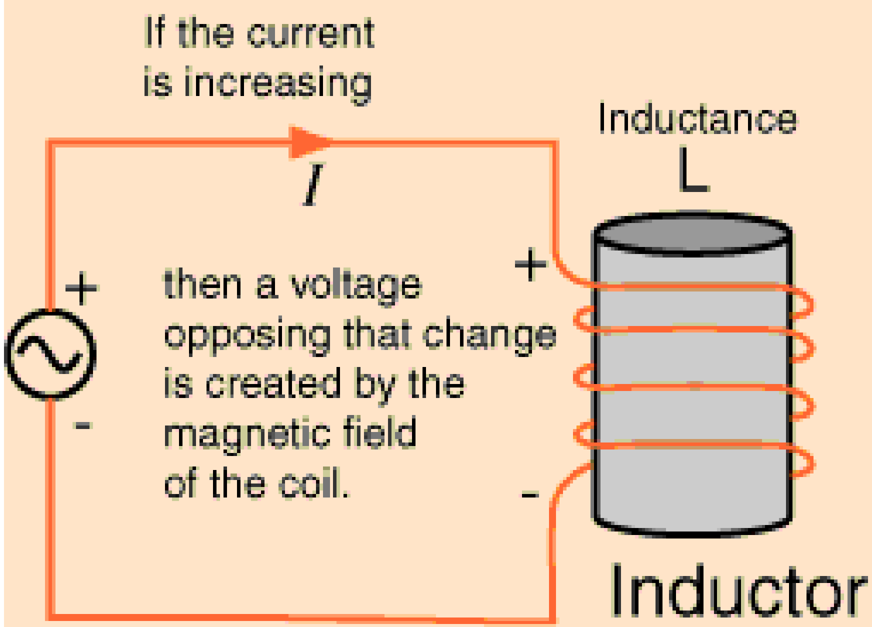
Faraday’s law of induction



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.

Faraday’s law of induction - inductance

Inductors



Inductance is typified by the behavior of a coil of wire in resisting any change of electric current through the coil.

Arising from Faraday's law, the inductance L may be defined in terms of the emf generated to oppose a given change in current:

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

Unit for L: $\frac{\text{volt second}}{\text{ampere}} = \text{Henry}$

Lecture 6: magnetism, electromagnetism

- comments to units

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:

$$T = \frac{Wb}{m^2} = \frac{N}{C \cdot (m/s)} = \frac{N}{A \cdot m}$$

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

In the older system CGS:

- The cgs unit is a *Gauss* (G)
  - $1\ \mathrm{T} = 10^4\ \mathrm{G}$

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:

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

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:

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

electroagnetism – 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 lecture – you can look forward to it! ;-)