Lecture 6: magnetism, electromagnetism

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- magnetic permeability,
- diamagnetic, paramagnetic and ferromagnetic material
- magnetic flux
- laws of electromagnetic interaction:
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  b. Biot-Savart law
  c. Amper’s law
  d. Faraday’s law of induction
- comments to units
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 → electromagnets

motion of an electron in atomic orbit → 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.
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 electromagnet 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 reenter 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.

$B$ is the field of magnetic induction (will be explained later on).
Field lines emanate from the + or N pole and reenter the - or S pole.
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.
Earth magnetic field is generated by the effect of movement of conductive masses in the outer Earth core – so called hydromagnetodynamic effects.
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** \( \mathbf{H} \) (unit, \([\text{A} \cdot \text{m}^{-1}]\)) and
- **magnetic induction** \( \mathbf{B} \) (unit, \([\text{T}] = \text{tesla}\));

Relation between them is given by this simple equation:

\[
\mathbf{B} = \mu \mathbf{H},
\]

where \( \mu \) – **magnetic permeability**, (unit: \([\text{H} \cdot \text{m}^{-1} = \text{N} \cdot \text{A}^{-2}]\)),

it describes the ability of a material to be magnetized by the action of an outer magnetic field.

We use also **relative magnetic permeability**:

\[
\mu_r = \frac{\mu}{\mu_0} \implies \mu = \mu_r \cdot \mu_0
\]

\( \mu_0 \) – permeability of vacuum (free space) or magnetic constant \((4\pi \cdot 10^{-7} \text{ H} \cdot \text{m}^{-1})\).

Comment: Units tesla and henry will be explained later on.
Magnetic intensity $\mathbf{H}$ ([A\cdot m^{-1}]).
Describes the measure of force effects (magnetisation effects) of the magnetic field. In comparison with magnetic induction, it does not include the reaction of the material to the outer magnetic field.

Magnetic induction $\mathbf{B}$ ([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 $\mathbf{H}$ vs. $\mathbf{B}$ is the so called hysteresis (we will come to it in a moment).
magnetism – basic quantities (premeability)

Based on the value $\mu_r$ ($\mu_r = \mu / \mu_0$) 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 $\mu_r = 0$. 

![Diamagnetic Material](image1.png) ![Paramagnetism](image2.png) 

superconductor:
magnetism – basic quantities (permeability)

Magnetic field ($B_0$)

Diamagnetic

Para/Ferromagnetic
**Table of Magnetic Materials**

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

diamagnetic ($\mu_r < 1$), paramagnetic ($\mu_r > 1$), ferromagnetic ($\mu_r >> 1$)
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
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):

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.

$B_s$ – 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 $H_C$).
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.

magnetism – basic properties (magnetic domains)

schematic visualisation of magnetic domains
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)

<table>
<thead>
<tr>
<th>Material</th>
<th>Curie temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron (Fe)</td>
<td>1043</td>
</tr>
<tr>
<td>Cobalt (Co)</td>
<td>1400</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>627</td>
</tr>
<tr>
<td>Gadolinium (Gd)</td>
<td>292</td>
</tr>
<tr>
<td>Dysprosium (Dy)</td>
<td>88</td>
</tr>
<tr>
<td>Mn Bi</td>
<td>630</td>
</tr>
<tr>
<td>MnSb</td>
<td>587</td>
</tr>
<tr>
<td>CrO₂</td>
<td>386</td>
</tr>
<tr>
<td>MnAs</td>
<td>318</td>
</tr>
<tr>
<td>EuO</td>
<td>69</td>
</tr>
<tr>
<td>Iron(III) oxide (Fe₂O₃)</td>
<td>948</td>
</tr>
<tr>
<td>Iron(II,III) oxide (FeOFe₂O₃)</td>
<td>858</td>
</tr>
</tbody>
</table>

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 $\Phi_B$ is the measure of flow of the magnetic field $\mathbf{B}$ through a given area $A$. Unit: weber, $[\text{Wb}] = [\text{T} \cdot \text{m}^2]$. 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:

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

and for closed irregular area $A$:

$$\Phi_B = \iiint_B \mathbf{B} \cdot d\mathbf{S} = 0$$

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

$$\vec{F} = q\vec{E} + qv \times \vec{B}$$

*Important: so called right hand rule for the 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.

\[ F = qvB \sin \theta \]

\[ \mathbf{F} \perp \text{plane of } \mathbf{v} \text{ and } \mathbf{B} \]
Lorentz force

\[ \vec{F} = q\vec{E} + q\vec{v} \times \vec{B} \]

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
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: \[ dB = C \frac{I}{r^2} \]

Resulting field \( \mathbf{B} \) we get as a result of integration along the wire.
Biot-Savart law

Result after integration (for a direct wire):

\[ |\vec{B}| = \frac{\mu_0 I}{2\pi r} \]

Here we have a next right hand rule – showing the direction of \( \vec{B} \).

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 \( \vec{B} \).
Biot-Savart law

The video from previous lecture:
https://www.youtube.com/watch?v=opJYLFvl-RE
Amper’s law (as a consequence of Biot-Savart law)

Also called as Amper’s circuital law.

\[ \int \vec{B} \cdot d\vec{l} = \mu_0 I \]

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

\[ \int \vec{B} \cdot d\vec{l} = \int \vec{B} \cdot dl = \vec{B} \cdot 2\pi r \]

When we now enter for the size of vector \( \vec{B} \) 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.

Simple d.c. Dynamo
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 $L$: $\frac{\text{volt second}}{\text{ampere}} = \text{Henry}$
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- 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:

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

In the older system CGS:
- The cgs unit is a Gauss (G)
- \( 1 \, T = 10^4 \, \text{G} \)
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:

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

unit Weber

Unit of **magnetic flux** $\Phi_B$.
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:

$$Wb = \frac{kg \cdot m^2}{s^2 \cdot A} = V \cdot s = T \cdot m^2 = \frac{J}{A}$$
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! ;-)