Electromagnetism

Review

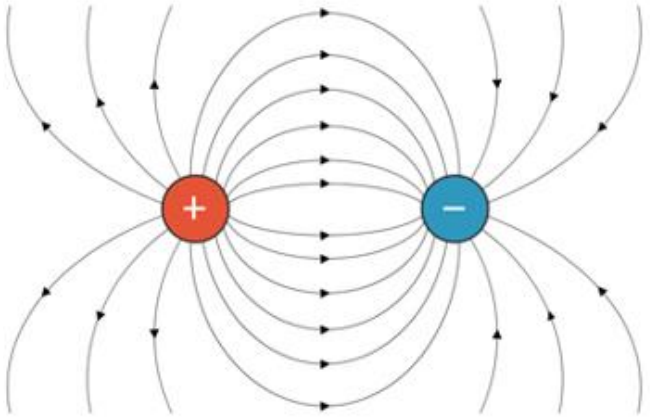
- Introduction
- Magnetic field strength
- Magnetic induction
- Permeability (para-, dia-, and ferromagnetic materials)
- Magnetic flux
- Force in a magnetic field
- Reluctance (magnetic resistance)
- Magnetic induction (static, dynamic (mutual and self) induction)
- Principles of Transformers (working principle, structure, equations, etc.)
- Magnetic cores (laminated, powdered, ferrite cores)
- Core and winding losses

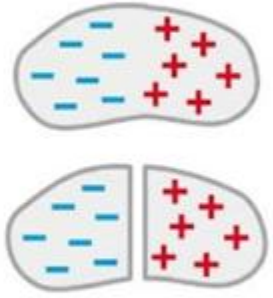
Introduction - Electric and Magnetic Fields

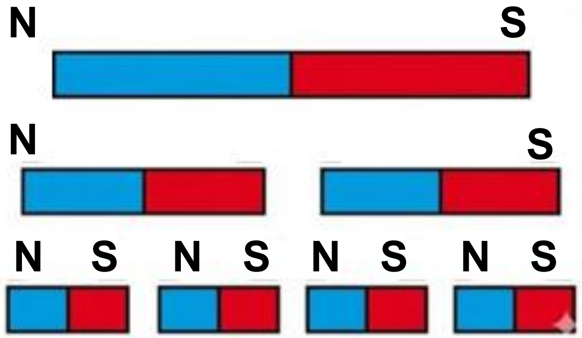
- The magnetic field is invisible to humans, so we can only detect it based on its effects:
    - Force
    - Current-carrying conductor
    - Inducing effect
- Electric fields and magnetic fields show several similarities
- The electric field is equal to the force acting on a unit positive charge, that is,

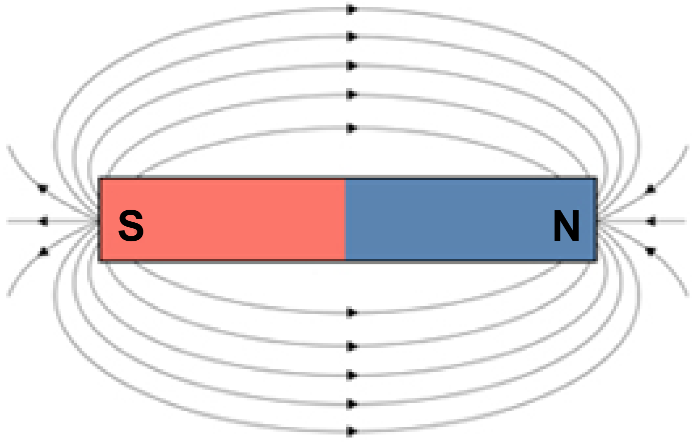
$$E = \frac{F}{Q}\ [N/C]\ or\ [V/m]$$

- An electric field can be separated into a sum of positive and negative charges (see: capacitor)
- If we cut a permanent magnet in half, we get another dipole
- In other words: a magnetic field consists of dipoles, and one magnetic pole cannot b separated from the other







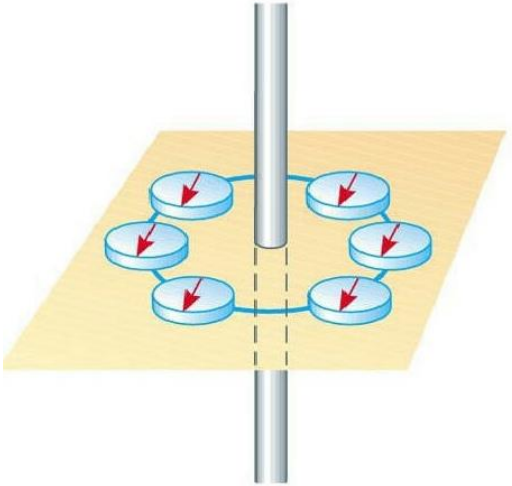


Quantities Characterizing a Magnetic Field – Magnetic Field Strength

- Take, for example, a conductor through which we flow current!
- Experiments show that when current flows through a conductor, a magnetic field forms around it.
- We can demonstrate a kind of force resulting from this using compasses.
- BUT! Even if we do not place compasses around the conductor, magnetic induction still occurs; the current still exerts an effect on its surroundings (though invisible to the eye).
- This effect depends on the magnitude (and direction) of the current and the geometry!
- We call this phenomenon magnetic field strength. Its symbol is H, and its unit of measurement is (A/m).
- Magnetic field strength (H) is therefore a vector quantity that characterizes the **intensity** of the magnetic field at a given point, independent of the material present.
- Around a straight conductor, the field strength will form in concentric circles (the field strength will be constant along a given contour), that is:

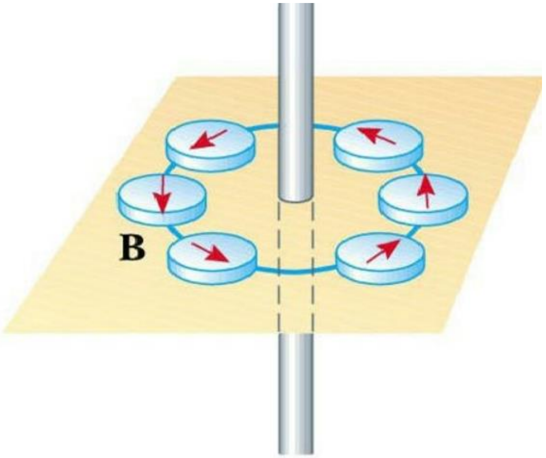
$$H = \frac{I}{2 \cdot \pi \cdot r},$$

  - where r is the distance measured from the wire (source)



(a)

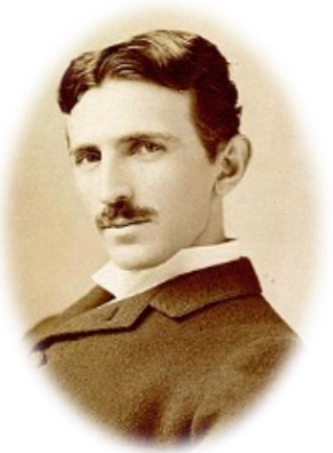
$I = 0$



(b)

$I > 0$

Magnetic induction



- Let's consider the previous experiment again!
- When we pass a current through the conductor, the compasses rotate (in accordance with the direction of the resulting magnetic field).
- What could be the reason? The compass is made of a material that is not magnetically neutral. The magnetic field applies a force to the compasses!
- This force is magnetic induction. Its symbol is B, and its units are (Vs/m^2) or (T) (Tesla) or (G) (Gauss). 1T = 10,000G
- Magnetic induction shows how the environment responds to the excitation.
- Magnetic induction is also a vector quantity that characterizes the **force** acting in a magnetic field.

The Relationship Between Magnetic Induction and Magnetic Field Strength

- The previous experiment raises several questions:
  - Does induction occur even if there is no compass present?
  - If there is no compass but some other material instead, what happens?
- Induction cannot be measured directly, but it can be established that magnetic field strength is not neutral with respect to materials: magnetic field strength (H) generates induction (B) in real materials (it “induces” the magnetic field), that is

$$B = \mu H$$

- Where μ is a material property: magnetic permeability.
- Accordingly, the magnetic field lines may run

In the air

$(B = \mu_0 H)$

In the magnetic core

$(B = \mu_0 \mu_r H)$

- So air (a vacuum) also has permeability, just a very low value : $\mu_o = 4\pi 10^{-7}\left(\frac{Vs}{Am}\right)$
- Relative permeability: μ_r
  - μ_r s the relative permeability, which indicates how many times greater the induction will be if the space is filled with a material rather than a vacuum $\left(\mu_r = \frac{\mu}{\mu_0}\right)$;
  - In reality—in the case of electrical machines—the combination of the two previously mentioned possibilities is typical (iron + air gap).

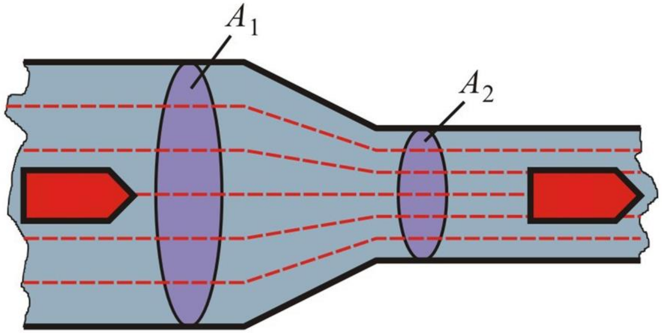
The Relationship Between Magnetic Induction and Materials

- The magnetic properties of different materials stem from their structure; they can be classified based on their relative permeability.
- **Diamagnetic** materials (μ_r >1) exhibit no magnetic properties in the absence of an external magnetic field. This effect is present in all materials, but very weakly. For example, if we bring a bar magnet close to such a material, the resultant of the forces acting on the piece of material produces an attractive interaction. In general, a paramagnet tends to move toward the area of higher magnetic field strength.
- **Paramagnetic** materials (μ_r <1) behave exactly the opposite way: these pieces of material are repelled by permanent magnets. A diamagnet tends to move toward areas of lower magnetic field strength
- The **ferromagnetic** effect ($\mu_r \gg 1$) is orders of magnitude stronger than the paramagnetic or diamagnetic effects. The reason for this is that, due to quantum mechanical interactions between individual atoms, within a ferromagnet, in larger regions known as domains, the elementary dipole moments all align in the same direction. Of course, in the absence of an external field, a macroscopic ferromagnet may not exhibit magnetic properties because the orientation of the domains is random. In the presence of a strong external field, these domains align, and when the field is removed, the random orientation is restored.

Diamagnetic		**Paramagnetic**		**Ferromagnetic**	
Material	μ_r	**Material**	μ_r	**Material**	μ_r
Water	0,99999901	Manganese	1,0004	Iron	3000-6000
Sulfur	0,99998	Aluminum	1,000022	Cobalt	100-400
Gold	0,99997	Tin	1,0000043	Nickel	200-500
Silver	0,999975			Permalloy	5e – 300e

Magnetic flux

- In previous studies, we learned about the concept of current density: current density indicates how much current is allowed to flow through a given cross-section (“surface”)
- A similar measure can be defined for magnetic circuits, which we call magnetic flux



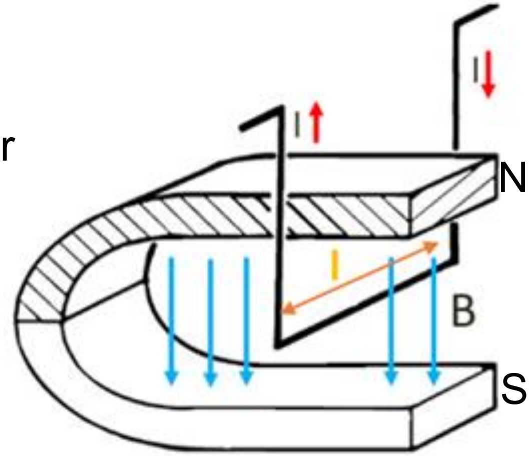
- Magnetic induction (B) indicates how dense the field lines are, while flux indicates the total number of field lines passing through a given area
- Symbol: Φ, units: (Vs/m²) or (Wb) (Weber)
- It can be calculated as:

$$\Phi = B \cdot A \cdot \cos(\propto),$$

  where α is the angle between the surface normal and the induction vector

- Magnetic field lines are vector quantities, so the relative orientation of the surface and the vectors is not irrelevant: the greatest flux occurs when the induction vectors are perpendicular to the surface
- From a practical standpoint (similar to current density):
  - The flux is greater if the number of induction vectors is the same on an equal surface area, or
  - More lines of force pass through a smaller surface area
- The smaller the surface area into which we “force” the flux, the more the iron core will heat up

Force in a magnetic field



- The interaction between two magnetic fields manifests as a force (attraction or repel)
- This force can be generated using a permanent magnet or a current-carrying conductor (e.g., a coil);
- If the current is perpendicular to the direction of the magnetic field, the force acting on the conductor is directly proportional to:
  - The current
  - The length of the conductor in the field
  - The magnetic induction (force line density):

$$F = BIl\ (N)$$

- If the magnetic field and the current are not perpendicular to each other, a smaller force is always generated; only the perpendicular component should be considered, that is:

$$F = BIl\sin(\theta)$$

Reluctance

- Reluctance refers to the magnetic resistance encountered by the magnetic flux;
- Just as resistance in electrical circuits impedes electric current, reluctance in magnetic circuits impedes magnetic flux
- The standard symbol for reluctance is R_m
- Analogy:

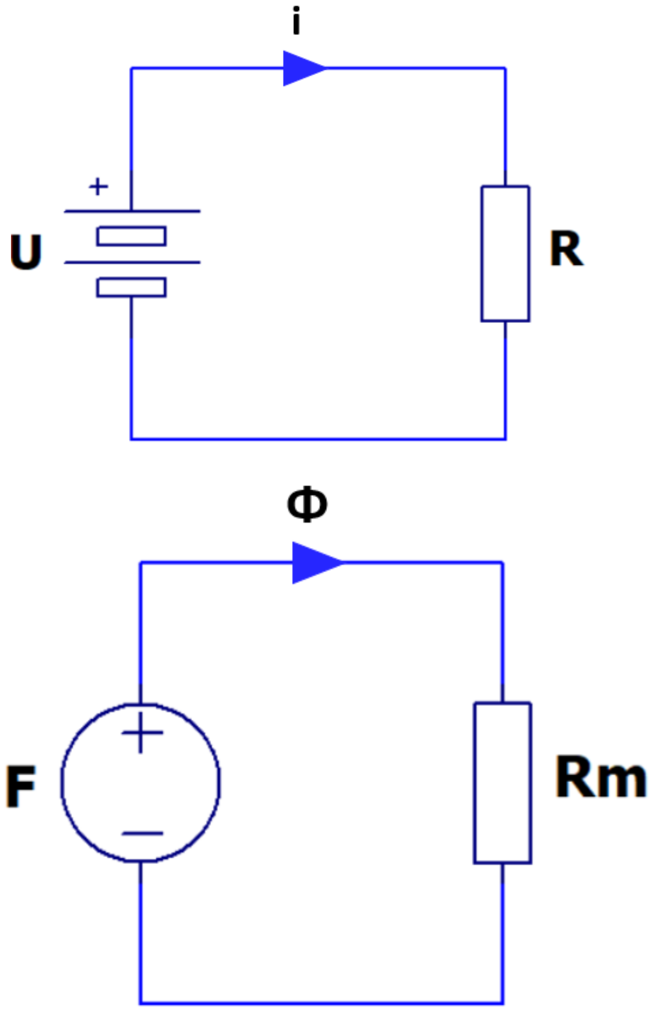
Electric circuit	Magnetic circuit
Voltage (*U*)	Magnetic excitation ($\theta = N \cdot I$)
Current (*I*)	Magnetic flux (*Φ*)
Resistance (*R*)	Reluctance (R_m)

- Magnetic Ohm's Law:

$$\Phi = \frac{N \cdot I}{R_m}$$

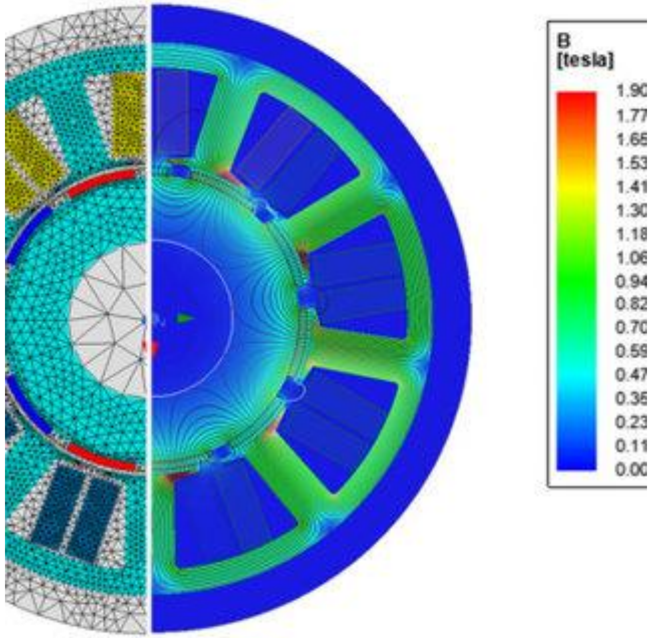
- The value of the reluctance depends on the material's properties and dimensions:

$$R_m = \frac{l}{\mu \cdot A} = \frac{l}{\mu_0 \cdot \mu_r \cdot A}$$



Finite element simulation for magnetic circuits

- The behavior of electric and magnetic fields is described by Maxwell's equations:
  - Solving these equations "by hand on paper" is not feasible in real-world cases
  - Nonlinear equations (e.g., BH characteristics)
- Finite element simulation (FEM):
  - The geometry is divided into a finite number of elements (for planar problems, for example, into triangles or quadrilaterals; for spatial problems, possibly into prisms or tetrahedrons)
  - In areas where the result may be critical to the solution, the "fineness" of the mesh is higher; where changes are expected to be smaller, larger elements are chosen

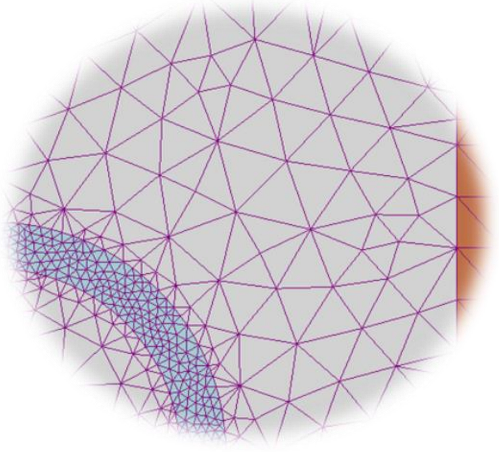


$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \times \vec{B} = \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t} + \mu_0 \vec{J}$$

$$\nabla \cdot \vec{B} = 0$$

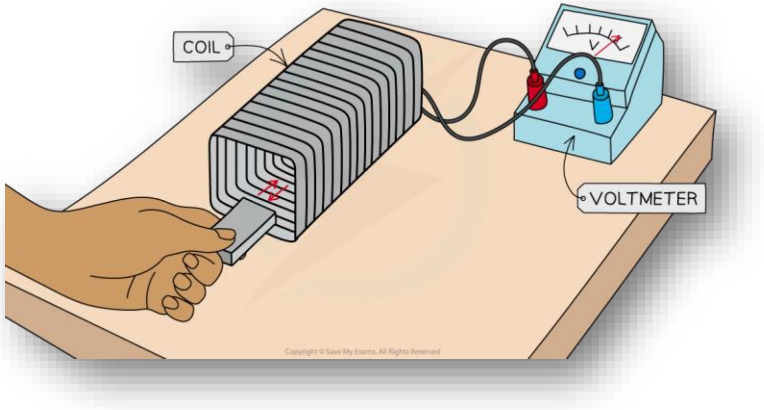


Source:
Researchgate,
wikipédia

Electromagnetic induction

- The phenomena associated with changes in a magnetic field are known as electromagnetic induction. The study of this phenomenon is attributed to Faraday (1831)
- There are several forms of electromagnetic induction

Dynamic induction



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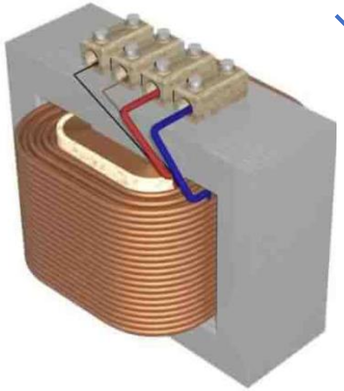
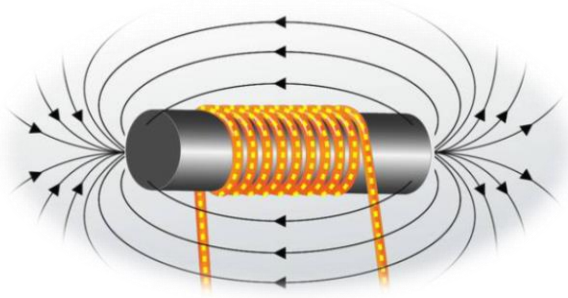
Static induction



Self induction



Mutual induction

Dynamic induction

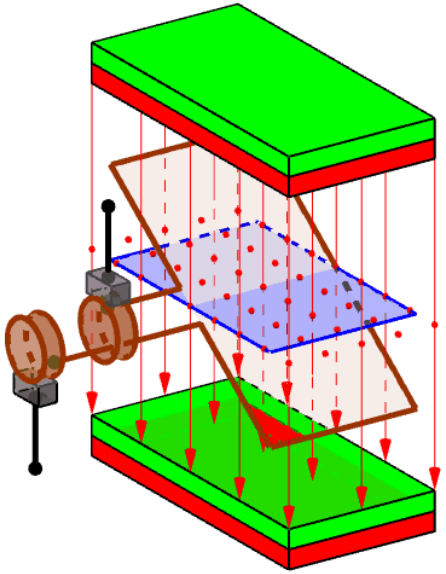
- It can be verified experimentally that if a conductor intersects (moves across) the magnetic field lines, a voltage appears between its ends, and if the circuit is closed, a current is induced.
- The quantities created in this way are called **induced voltage** and **induced current**.
- The magnitude of the induced voltage depends on the magnitude of the magnetic flux density, the length of the conductor loop, and the velocity of motion

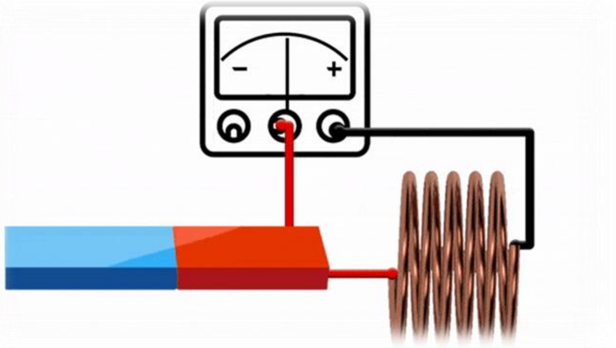
$$U_i = B \cdot l \cdot v$$

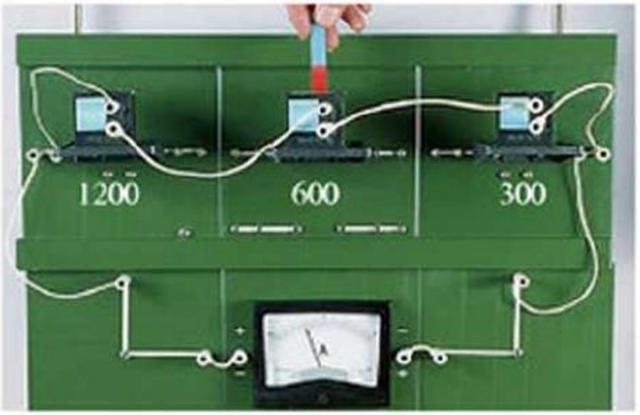
- For coils:

$$U_i = N \cdot B \cdot l \cdot v$$

- From the above, it can be concluded that the induced voltage is maximum when the conductor is perpendicular to the magnetic field lines (blue rectangle). If this is not the case, only the component perpendicular to the field lines must be considered!







Source:
netfizika.hu
Mozaik, Fizika 8

The direction of the induced voltage

- The induced voltage (current) always has a direction such that it opposes the motion or change that created it (Lenz's law).
- What does this mean?

Case 1: The magnet is approaching the coil

- The magnetic flux will increase.
- A current is induced in such a direction that it opposes the increase in flux

This is only possible if the "approaching side" of the coil becomes a **north pole**.
Since like magnetic poles repel each other, the coil will repel the approaching magnet.
The polarity of the coil can be determined using the **right-hand rule** (thumb points to the north pole, the fingers indicate the direction of current).
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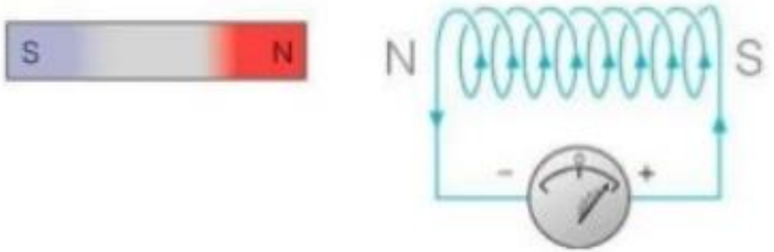
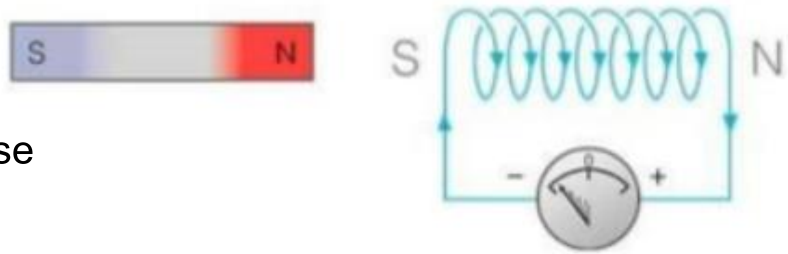


Case 2: The magnet is moving away from the coil

- The magnetic flux linkage with the coil is decreasing
- An induced voltage is generated in the coil. If the circuit is closed, a current flows, creating a magnetic field..

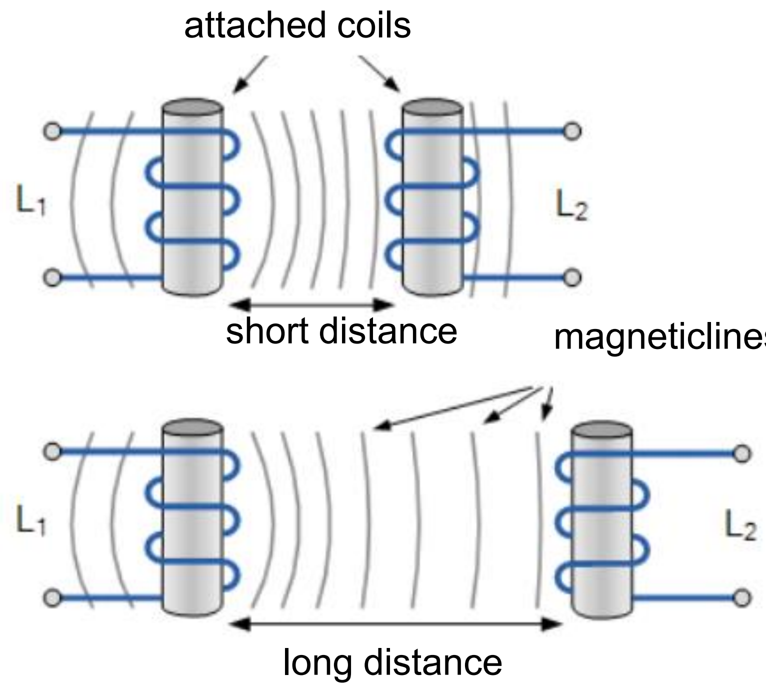
According to Lenz's law, the induced magnetic field acts in the opposite direction to the cause that created it. Therefore, the end of the coil closest to the magnet becomes a **south pole**.
This results in an attractive force between the coil and the magnet, opposing the separation.



Static induction - magnetic coupling

- Sstatic induction occurs when the magnetic field around a stationary conductor changes in time (for example, when the current of an electromagnet is changed).
- In this case, the magnetic elements (coil or magnet) do not move; instead, the magnetic flux (and current) changes over time.
- This is the principle behind the operation of transformers and wireless chargers.
- Two systems are said to be coupled if energy can be transferred from one to the other, meaning that the magnetic field lines produced by one coil also pass through the other coil
- Therefore, a coupling coefficient can be defined to describe the strength of interaction between the coils.
- The coupling is characterized by the factor *k*, which can take values between 0 and 1:
    - $k = 1$, perfect coupling (all flux lines are shared)
    - $k = 0$, no coupling (the coils are too far apart)
    - $0 < k < 1$, tight or loose coupling
- In practice, coupling is always less than 1, accounting for leakage flux.
- When two coils are coupled, a change in current in one induces a voltage in the other. This relationship is described by mutual inductance *m*:

$$M = k\sqrt{L_1 L_2}$$



Self-induction

- Self-induction is a phenomenon in physics where a coil generates a voltage "on its own
- This occurs when the strength of the current flowing through the coil changes (over time), which in turn alters the coil's own magnetic field.
- This process is the electrical equivalent of inertia.
- When current flows through a coil, a magnetic field forms around it. If this current changes (increases or decreases), the flux (Φ) inside the coil will also change. However, according to Faraday's law of induction, any change in flux induces a voltage. Since this change in flux is caused by the coil's own current, the phenomenon is called self-induction.

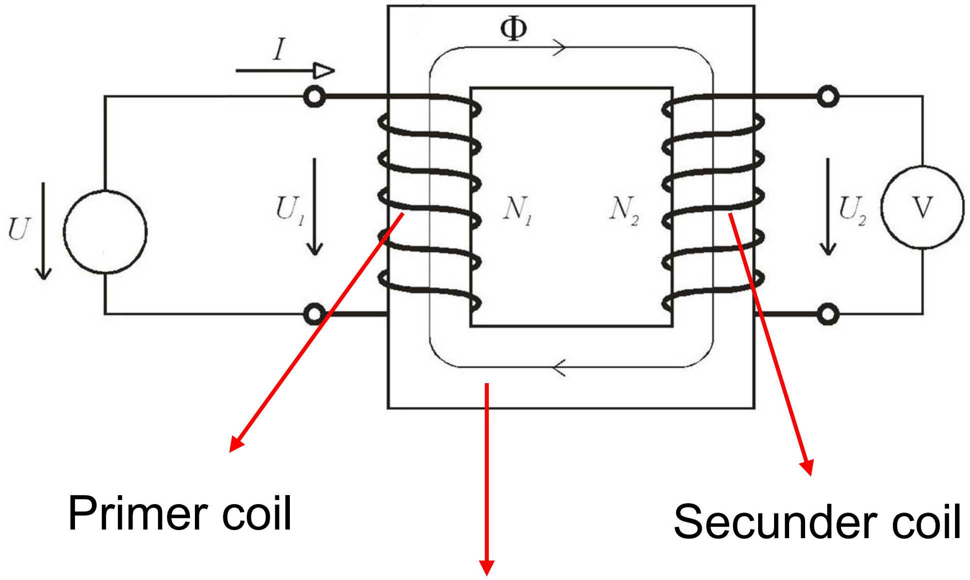
$$u_i = -\frac{d\psi}{dt} = -N\frac{d\Phi}{dt}$$

$$u_i = -N\frac{N}{R_m}\frac{di(t)}{dt} = -\mathrm{L}\frac{dI}{dt}$$

- Where do we encounter this in practice?
  - **Fluorescent lamp starter**: In older-style fluorescent lamps, the sudden interruption of a coil (choke coil) creates the high-voltage surge that ignites the gas.
  - **Spark plug in a car**: A car's ignition coil also uses the principle of self-induction: when the low-voltage current is interrupted, a spark of tens of thousands of volts is generated.
  - **Relay protection**: When an electromagnetic relay is turned off, self-induction can damage the control electronics, so a protective diode is typically connected in parallel to "dissipate" this sudden voltage surge.

Transformer Structure

- A transformer is an electrical machine that operates on the principle of static induction, converting electrical power with a given alternating voltage and current into electrical power with a different alternating voltage and current
- Efficiency: 95–99% (see below for losses)
- Components:



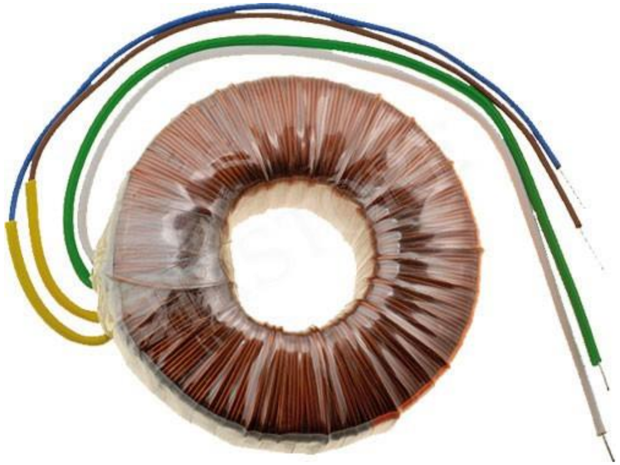
Primer coil

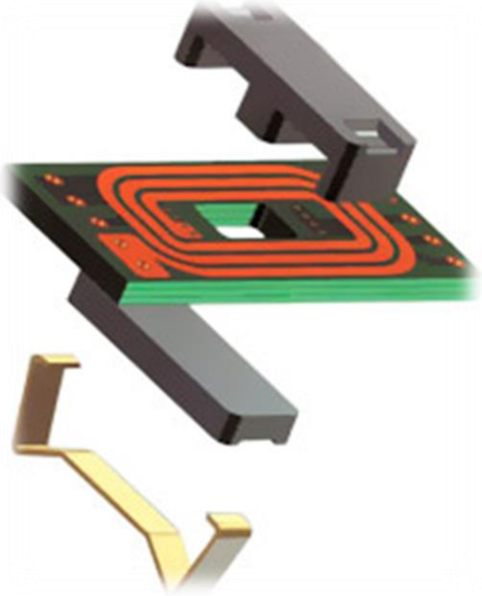
Magnetic core

Secunder coil

Forrás: http://tudasbazis.sulinet.hu;wikipédi

Transformers in Practice





How a transformer works

- Let's apply an alternating voltage to the primary coil. As mentioned earlier, this creates a varying magnetic flux in the core:

$$u_p(t) = N_p \frac{d\phi(t)}{dt}$$

- As a result of the changing flux, a voltage is induced in the secondary winding, that is:

$$u_{sz}(t) = N_{sz} \frac{d\phi(t)}{dt}$$

- Neglecting leakage flux, the flux in both coils is the same, i.e.:

$$\frac{U_p}{U_{sz}} = \frac{N_p}{N_{sz}} = a$$

$$P_p = P_{sz}$$

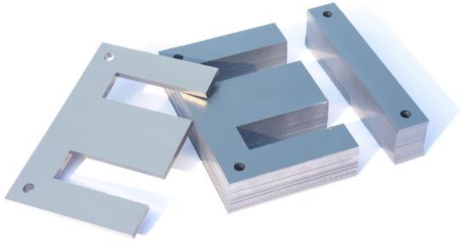
$$U_p I_p = U_{sz} I_{sz}$$

$$\frac{U_p}{U_{sz}} = \frac{I_{sz}}{I_p}$$

- Observations:
  - The number of turns is directly proportional to the ratio of voltages
  - Voltage (and turns) is inversely proportional to current. For example, if the primary side has a higher voltage, it corresponds to a lower current, while on the secondary side it is the opposite, since $P_p = P_{sz}$
  - A transformer does not operate on direct current

Transformer core design options:

LAMINATED
CORE



IRON-BASED
AMORPHOUS CORES

POWDER
CORE

FERRIT CORE

FREQUENCY

Source: researchgate.com

Laminated core

- Because of the mains frequency, this is the most widely used core type

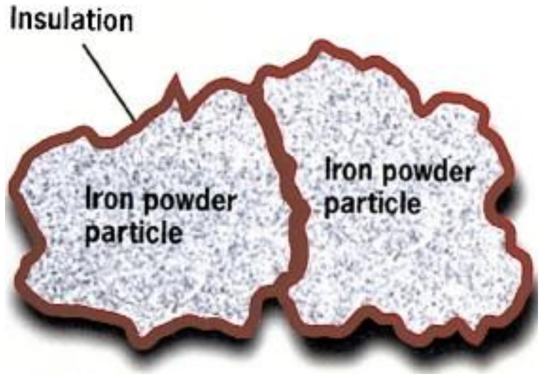
↓

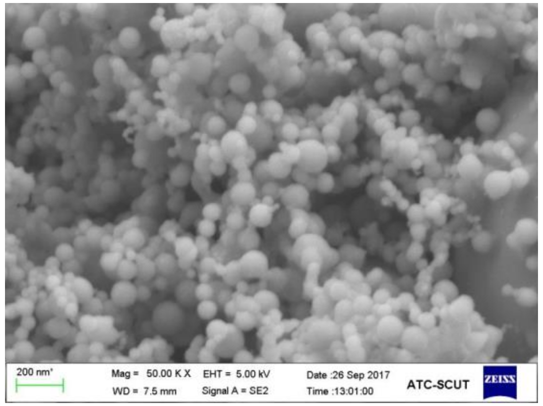
Therefore, it is typically used at 50/60 Hz, or at lower harmonics (a few kHz)

- Advantages:
  - Relatively low cost
  - Can be welded
  - Relatively high maximum flux density (about 1.5–1.8 T)
  - Stable temperature dependence
- Disadvantages:
  - Laminated structure (stacking requirement)
  - Losses (W/kg)
  - Noise
  - Limited usable frequency range

Powder core

- It is typically used for higher frequencies: the fundamental harmonic is up to about 10 kHz, and harmonics up to about 50 kHz.
- Technical construction:
  - The iron core material is first ground into powder, then the particles are oxidized. The resulting powder is mixed with a binding material and pressed into a mold under high pressure (the binder also provides electrical insulation)
  - The resulting core material has significantly lower losses than “traditional” laminated transformer steel
  - The smaller the grain size, the better the loss characteristics
  - However, the gaps between the grains affect permeability: the smaller the gap, the more “compact” the iron, and the higher its permeability (μ_r)
  - It is often referred to as a **distributed air-gap core**
  - Due to this “distributed” air gap, the core enters saturation later (see later slide)
- There are many types of powder cores available on the market under various brand names.





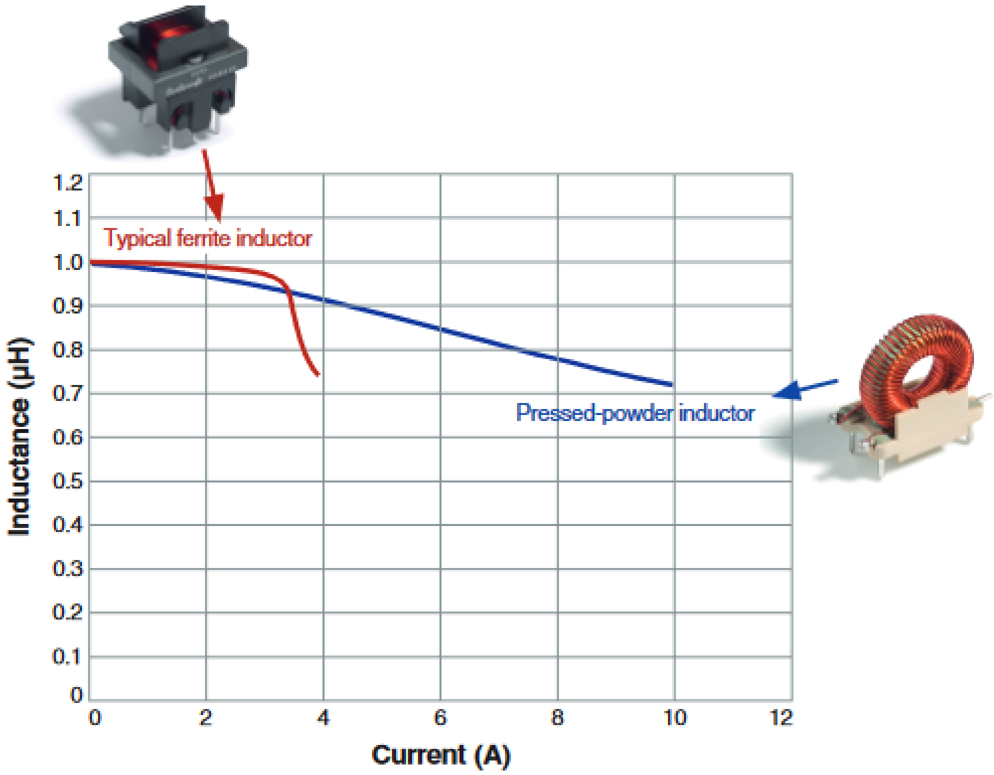
Ferrit core

- Ferrites are polycrystalline ceramics composed of iron oxide (Fe_2O_3). To this base material, additional oxides or carbonates are added, such as:
  - manganese (Mn)
  - nickel (Ni)
  - zinc (Zn)

- The materials are pressed and then sintered (fired at high temperature)
- Metal oxides (i.e., metal oxides) are classified as ceramics, which is where the name comes from.
- Advantages:
  - Most ceramics have high electrical resistivity, which reduces eddy current losses < 0,5T
  - High magnetic permeability (typically μ_r=40….10000)
- Disadvantages:
  - Low magnetic flux density (typically < 0.5 T)
  - Brittle (easily broken)

- At high frequencies (typically RF range: kHz to MHz), losses can still be significant, although relatively low compared to other materials in this range
- They are typically used in high-frequency transformers for switching power supplies, as well as in filter and tuning inductors, especially in power electronics applications

Comparison of Powder Cores and Ferrite Cores



Powder core	Properties	Ferrit core
Relatively cheap	Permeability (μ_r)	Relative expensive
Relatively high core losses at high flux density.	Core losses (P_v)	Relatively low core losses at high flux density.
Soft saturation	Others	Brittle (e.g., edges/corners)

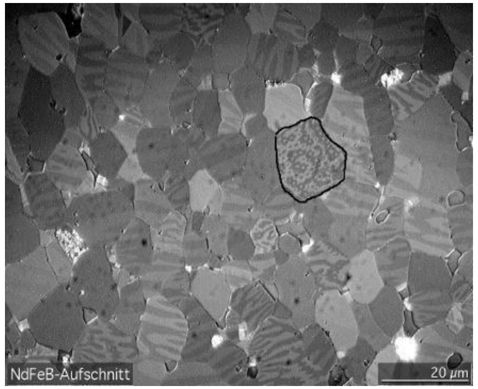
Source: coilcraft.com

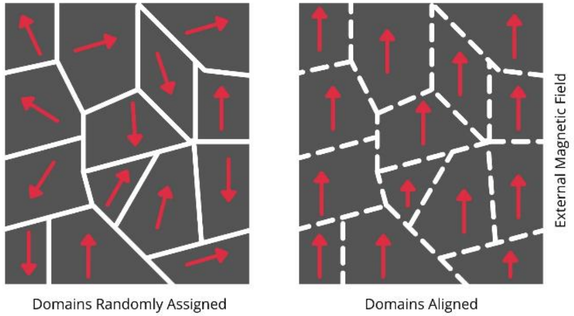
Core losses

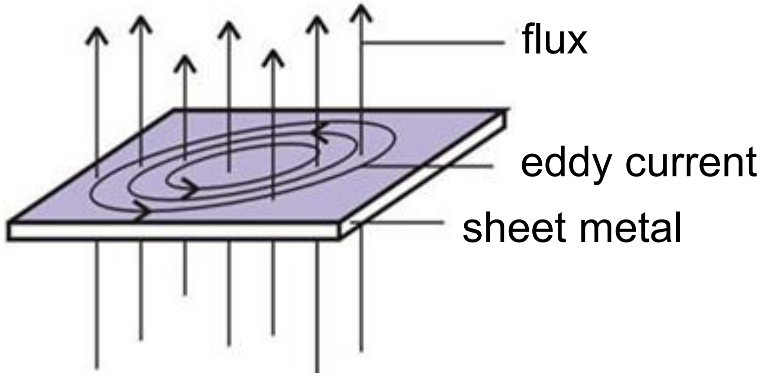
- Core losses consist of two parts:

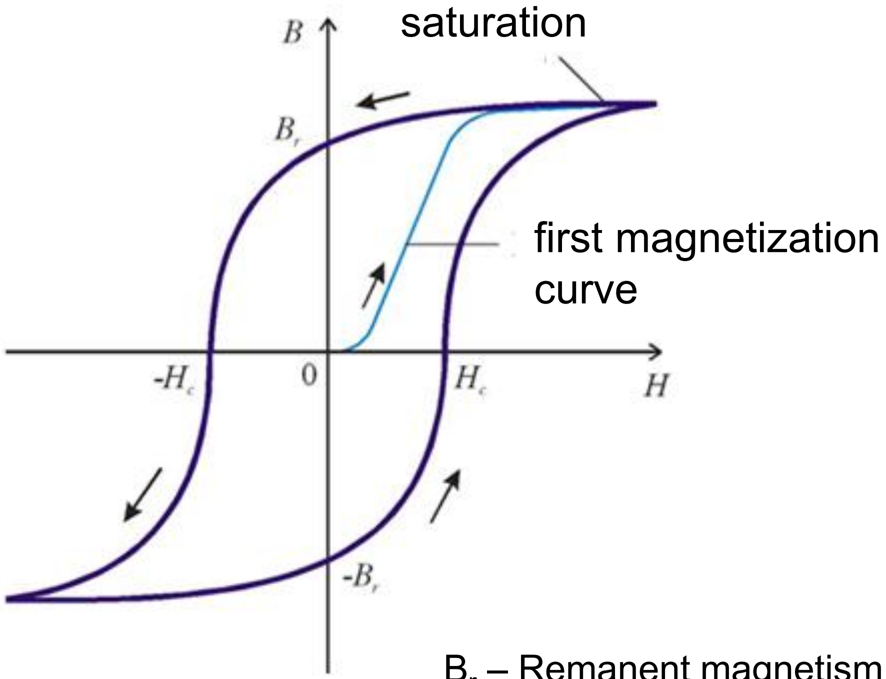
$$P_{core} = P_{hyst} + P_{eddy}$$

- **Hysteresis loss:**
  The molecular magnets (elementary magnetic domains) in the iron continuously try to align with the alternating magnetic field. The magnitude of this loss depends on the material, frequency, and maximum flux density.
- **Eddy current loss:**
  Since the core is made of metal, it conducts electricity. The changing magnetic flux also induces a voltage inside the core (like in a single-turn coil). Because the iron has a large cross-section and low resistance, large circulating currents can flow, which causes significant heating of the core. This loss can be reduced by decreasing the thickness of the laminations. The sheets must be electrically insulated from each other (e.g., by varnishing).







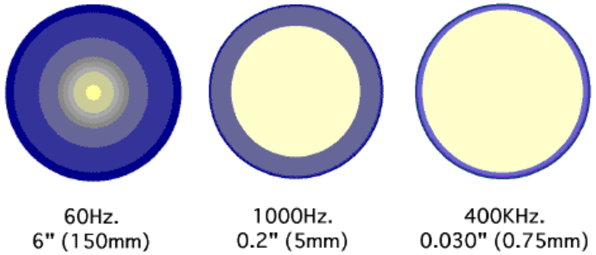


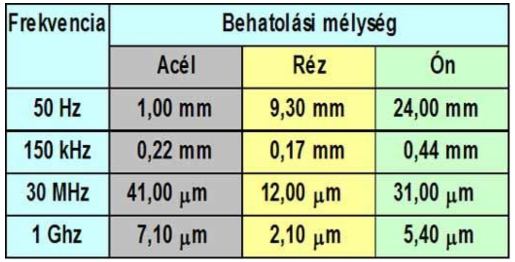
B_r – Remanent magnetism
H_c – Coercive field strength

Winding losses

- The winding has an important parameter called **current density**, which is closely related to the cross-sectional area of the winding wire.
- During design, a good starting value can be **3–5 A/mm²** (depending on the application).
- Another important characteristic of the winding is its **DC resistance**, which is typically in the **mΩ range** (measured using four-wire resistance measurement, mΩ meter).
- At higher frequencies, the conductor in the magnetic circuit does not conduct current through its full cross-section:
- (This is due to the **skin effect**, where current is concentrated near the surface of the conductor.)

Skin effect





Frekvencia	Behatolási mélység		
	Acél	Réz	Ón
50 Hz	1,00 mm	9,30 mm	24,00 mm
150 kHz	0,22 mm	0,17 mm	0,44 mm
30 MHz	41,00 μm	12,00 μm	31,00 μm
1 Ghz	7,10 μm	2,10 μm	5,40 μm

Proximity effect