

Magnetic field

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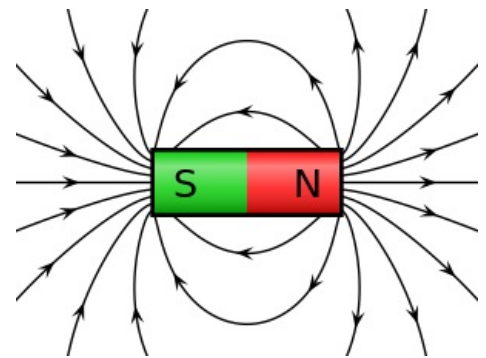
Magnets are the generic name for natural iron ores that have the ability to attract iron objects and other substances with the same ability. The name was derived from the Greek city of Magnesia, near which these minerals were found.

These substances create a **magnetic field**, however, this physical field can be created in other ways - generally, magnetic field sources are divided into:

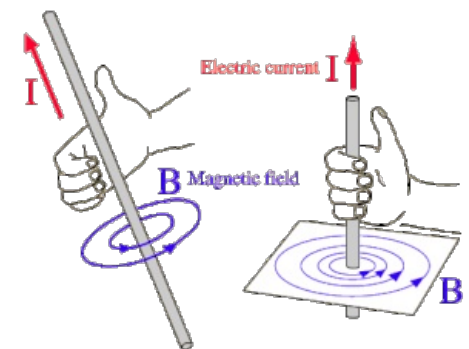
- **Permanent magnets** - substances that create a magnetic field without requiring an external influence. Magnetic magnets are magnets that do not require any external influence. They can be made from ferromagnetic substances.
- **Electromagnets** - need an electric current to create a magnetic field. These are electrically conductive materials. For example, a coil with a ferromagnetic core is used as an electromagnet.

Previously, magnetism was not associated with electricity. The first to notice the connection was H. Ch. Oersted, who, while working with an electrical circuit, noticed that the needle of a compass moved when the circuit was connected. Today we know that the magnetic field is closely related to the electric field, as expressed by Maxwell's equations. Their close connection is also demonstrated by electromagnetic induction. But there is also an electromagnetic field, which must not be confused with the above-mentioned types of fields.

Magnetic fields are primarily divided into stationary and non-stationary fields.



Magnet



Ampers right hand thumb rule

Stationary magnetic field

A stationary magnetic field is a magnetic field whose properties do not change over time. The vector B of the magnetic induction is constant in magnitude and direction at a given point in the field. The source of this field may be permanent magnets or a stationary conductor in which a constant electric current flows.

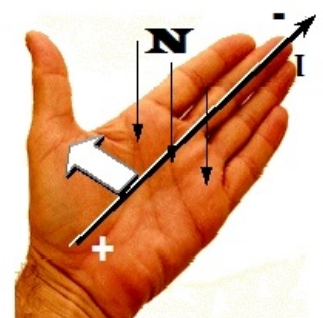
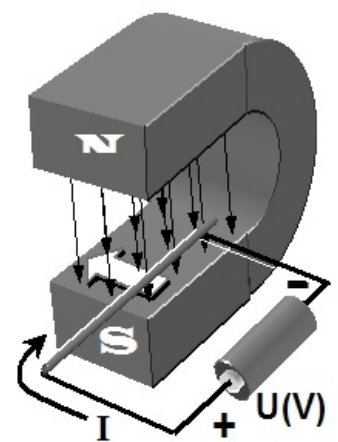
Magnetic induction lines

We can use **magnetic induction lines** to represent the magnetic field. The magnetic induction line is always a closed curve whose tangent at a given point has the direction of the axis of a small magnet placed at that point. Thus, for a straight conductor, we observe concentric circles centered at the point of intersection of the conductor with a plane perpendicular to it, in which the circle lies.

Inside the coil the magnetic induction lines are parallel to each other with the axis of the coil. Outside the coil, the magnetic field is similar to that of a bar magnet. Here the magnetic induction lines form closed curves emerging from one end of the coil (corresponding to the north pole of the magnet) and entering the opposite end (the south pole).

Due to the fact that magnetic induction lines are closed curves, we can also use the term vortex field for magnetic fields - there are no magnetic charges from which the field lines (i.e. magnetic induction lines) begin and end. This feature would apply to an electric field, which we also call a rarefied field.

To determine the orientation of the induction lines around an electric conductor, **Ampere's right-hand rule** for a straight conductor helps us, where the fingers of the right hand show the desired orientation of the magnetic induction lines, while the thumb points in the same direction as the current in the conductor. In a modified version, the rule can also be applied to a coil (**Ampere's right hand rule for a coil**), where the bent fingers indicate the direction of the current in the coils and the thumb indicates the orientation of the magnetic induction lines.



Flemings left hand rule

Magnetic force

The magnetic force F_m is the basic manifestation of the force action of the magnetic field. It is determined by the formula **$F_m = B \cdot I \cdot l \cdot \sin \alpha$** .

The direction of the force exerted by an external magnetic field on a conductor located in that field is determined by **Fleming's left hand rule**: If we place our open left hand against a straight conductor with the fingers pointing in the direction of the current and the induction lines entering the palm, the withdrawn thumb points in the direction of the force exerted by the magnetic field on the conductor carrying the current.

Magnetic induction

It is a vector quantity (with direction determined by the tangent to the given induction line) **B** with unit T (Tesla), where $T = N \cdot A^{-1} \cdot m^{-1}$, which characterizes the magnetic field force on the current carrying conductor. It is always constant for a given homogeneous field.

Magnetic field of current-carrying conductors

From general knowledge, we know that a magnetic field is created in the vicinity of the conductor through which the current flows. We also know that the magnetic field exerts a force on the current carrying conductor. If we place two straight parallel conductors close to each other through which current will pass, they will exert a force on each other and two variations can occur.

Currents of the same direction will pass through the conductors and the two conductors will attract each other.

Currents of opposite direction will pass through the conductors and the two conductors will repel each other.

We arrived at this using Ampère's right hand rule to determine the orientation of the induction lines. We used this knowledge to determine the direction of the force that will act between the conductors due to Fleming's left hand rule.

The formula **$F = (\mu/2\pi) \cdot (I_1 \cdot I_2 \cdot l) / d$** is used to determine the magnitude of the applied force.

Magnetic field of the coil

By coil we mean a wound wire. In practice, we use coils of various shapes and designs (e.g. with or without a core). The magnitude of the magnetic induction depends on the number of turns of the coil and the electric current that passes through the coil. The problem arises with the creation of a homogeneous magnetic field. There are three basic types of coils based on their shape and dimensions. Almost homogeneous magnetic fields are found in **Hemholtz coils**. Hemholtz coils are narrow circular coils with a common axis whose mutual distance is equal to the radius of the coils. They are used in a Wehnelt tube. This allows the movement of electrons in a magnetic field to be observed. A **solenoid** is a long cylindrical coil with a high number of turns whose diameter is much smaller than the length of the coil. The **toroid** is obtained by twisting the solenoid into a ring.

Particles with charge in a magnetic field

We know the formula for calculating the magnetic field strength for a straight conductor $F_m = B \cdot I \cdot l \cdot \sin \alpha$ and we also know that in a metallic conductor the electric current is made up of electrons with charge $Q = -eN$, where N is the number of electrons. The resulting formula for calculating the force on a particle with a charge in a magnetic field will be **$F_m = B \cdot Q \cdot v \cdot \sin \alpha$** .

Lorentz force

In an electromagnetic field a particle with a charge moves, on this particle the electric force F_e and the magnetic force F_m act simultaneously. Therefore, the resulting force acting on the particle will be **$F = F_e + F_m$** .

Inductance of the coil

Coil inductance **L** [H] is a quantity characterizing the magnetic properties of the coil. It is, among other things, an important parameter of an electrical circuit (like resistance **R** and capacitance **C**). Applying Faraday's law of electromagnetic induction, we obtain the relation **$U_i = - \Delta \Phi / \Delta t = - \Delta I / \Delta t$** expressing that a voltage of 1V is induced in a coil if it has an inductance of 1H and a current change of 1A occurs in 1s. The energy of the magnetic field is expressed by **$E_m = 1/2 L I^2$** .

Intensity

The magnetic field strength **H** [A/m] can be expressed by **$H = F_m / l = IN / l$** .

Permeability of the environment

The permeability of the medium **μ** is a quantity characterizing the medium in which the magnetic field is generated by an electric current. In a vacuum, if there is a magnetic field, we speak of the permeability of the vacuum **μ_0** - **$\mu_0 = 4\pi \cdot 10^{-7} N \cdot A^{-2}$** .

Non-stationary magnetic field

In contrast, the properties of the **non-stationary magnetic field** change with time, thus the magnetic induction changes. Sources of this field include a non-moving conductor with a time-varying current, a moving conductor with a current (both time-varying and constant), or a moving permanent magnet or electromagnet.

Electromagnetic induction

Due to the non-stationary magnetic field, an induced electric field is created and this phenomenon is called **electromagnetic induction**. In this case, an induced electric voltage U_i is generated at the ends of the coil and an induced electric current I_i flows through the entire closed circuit. *Induction plate* - Just below the plate is a coil powered by high frequency alternating current. This periodically alternating current is used to indicate the current in the conducting pan and, because the pan has a non-zero resistance, it generates the heat necessary to cook food. Importantly, the induction pan remains unheated. *Electric guitar pickup* - An oscillating metal string, acting as a magnet, indicates a non-stationary magnetic field in its surroundings and this in turn changes the direction of the magnetic induction flux in the coil at the same frequency as the oscillations of the string and transmits these oscillations to the amplifier, the speaker.

Magnetic induction flux

The **magnetic flux** is a scalar quantity Φ with unit Wb (weber), which is used to quantitatively describe electromagnetic induction. We need a homogeneous magnetic field, a planar surface of content S , a normal n to the surface S , a magnetic induction vector B , and the angle α that the normal n makes with the vector B - we get the formula $\Phi = B \cdot S \cdot \cos \alpha$.

In connection with electromagnetic induction it is necessary to mention **Faraday's law of electromagnetic induction** expressed by the equation $U_i = -d\Phi/dt$, where U_i denotes the instantaneous value of the voltage. The minus sign symbolically represents **Lenz's law** of the direction of the induced electric current, which counteracts with its magnetic field the change in the magnetic flux that induces it.

Foucault's eddy currents

Induced currents arising in massive conductors (e.g. sheet metal) moving in a magnetic field, or those placed in a time-varying magnetic field that counteracts the change that induced it. Application - *induction brake in locomotives, buses, trams, elevators...*

Self induction

In connection with the coil, we also encounter a phenomenon called self-induction (denoted by the letter L), in which an induced electric field is created in the conductor by changes in the magnetic field. These changes produce a current through the conductor. Uses: *inductor* - This is a coil that has a closed ferromagnetic core and a high inductance. It has many uses in electrical engineering.

Transitional agency

It occurs in the case, when the electric circuit, in which the coil with high inductance L was located, was disconnected or connected. When the connection is made, an induced voltage is produced which has the opposite polarity to that of the source voltage (according to Lenz's law). When the circuit is disconnected, an induced voltage is produced that has the same polarity as the source but a significantly larger magnitude.

Magnetic properties of substances

The magnitude of the magnetic induction depends on the permeability of the medium that forms their core. The magnetic induction of a coil wound on a steel core is higher than without a core. The relative permeability is determined by the properties of the atoms of which the substance is composed.

The electrons in the atoms create an elementary magnetic field which produces the resulting magnetic field of the atom. According to the arrangement of electrons in an atom, substances are divided into 3 groups:

1) Diamagnetic substances

Diamagnetic substances are composed of diamagnetic atoms and the relative permeability is slightly less than one. Hence, these substances slightly weaken the magnetic field and repel from the magnet. Examples include inert gases, gold, copper, mercury, etc...

2) Paramagnetic substances

These are substances composed of paramagnetic atoms whose relative permeability is slightly greater than 1. They slightly amplify the magnetic field. A paramagnetic atom (molecule) has a permanent magnetic moment even in the absence of an external magnetic field. This is usually due to the presence of an unpaired electron in the electron shell. Dipoles do not interact in paramagnets and are randomly oriented in the absence of an external field, therefore the magnetic moment is zero. If the substance is in a magnetic field, the dipole is rotated in the

direction of the magnetic field, thus producing a magnetic moment. These substances cannot be permanently magnetized. Examples include potassium, sodium or blue rock (copper and blue rock belong here because of their chemical bonding).

3) Ferromagnetic substances

These are substances composed of paramagnetic atoms that arrange themselves into magnetic domains. Unlike paramagnetic substances, ferromagnetism is explained by magnetic domains. Their relative permeability is much higher than 1 (on the order of 10^2 to 10^5). Even in the vicinity of a weak magnetic field, the magnetic field will be strengthened and the substance will be magnetized.

The cause of magnetization of a substance is the action of exchange forces between neighbouring atoms. Due to their influence, even without a magnetic field, a consensual arrangement of magnetic fields occurs in a small region of the substance. During this spontaneous magnetization, microscopic domains are formed - **magnetic domains** (volume 10^{-3} - 10^{-10} mm³) - these are actually atoms that are arranged in the same direction. Magnetic domains are magnetically saturated regions of a ferromagnetic substance and are oriented randomly. Under the action of a magnetic field, these domains orient themselves in a conformal manner and the substance acquires the properties of a magnet. By magnetization, the volume of the domains gradually increases until the substance is magnetically saturated (i.e., when the domains are arranged consensually and the domain structure disappears). In contrast, in paramagnetic substances, a parallel arrangement of magnetic moments - i.e. magnetic saturation - cannot be achieved (the consensual arrangement of atoms and thus the consensual orientation of magnetic fields is prevented by their thermal motion).

Ferromagnetic substances are for example Fe, Co, Ni, or their alloys. Ferromagnetic substances include also ferrimagnetic substances (in other words, ferrites), which differ from ferromagnetic substances by their greater resistance. These are compounds of iron oxide or other metals (Mn, Ba).

Ferromagnetic substances are of great importance in the manufacture of transformers and electromagnets (they form the cores of coils). Ferromagnetic substances are used in low-current electrical engineering or as permanent magnets.

Properties of ferromagnetic substances

Ferromagnetism occurs when the substance is in a crystalline state (in the liquid or gaseous state they behave like paramagnetic substances).

For every ferromagnetic substance there is a Curie temperature above which it becomes a paramagnetic substance. The resulting magnetic domains break down again into individual atoms, and the formation of the domains is prevented by the thermal motion of the particles.

Usage

Thanks to the magnetic properties of the Earth, we can, for example, use a magnet as a compass for orientation. But this is not the only use of knowledge of magnetic field phenomena in engineering practice. Magnetic recording of sound or image signals is also known - the medium can be, for example, a floppy disk. One of the most important medical applications is **magnetic resonance imaging** (MRI).

BOLD fMRI

Blood oxygen level dependent functional magnetic resonance imaging is one of the tools for visualization of brain anatomical structures. Unlike standard MRI, it detects dynamic changes. These dynamic changes are caused by variations in oxyhemoglobin and carbaminohemoglobin based on their different properties. Deoxyhaemoglobin has paramagnetic properties, i.e. magnetic inhomogeneities are created in areas of higher concentration, resulting in a faster loss of energy of excited protons, resulting in a greater local loss of radiofrequency signal. The signal detection is processed by Echo Planar Imaging (EPI). The method allows to decode the signal from the whole slice or volume after one or several radiofrequency pulses by using rapid changes in the magnetic field. The detected signal is divided into a finite number of samples. In contrast to deoxyhemoglobin, oxyhemoglobin has weak diamagnetic properties and a very small effect.



NPH MRI 272 GILD

Physiological principle of BOLD fMRI

The brain does not store sugar as a primary source of energy. When neurons show activity, they actively pump ions across the membrane. This activity requires energy that comes from glucose. Higher blood flow brings more glucose and thus more oxygen via oxyhemoglobin. The change in blood flow is localized 2-3 mm from the site of neural activity.

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Related articles

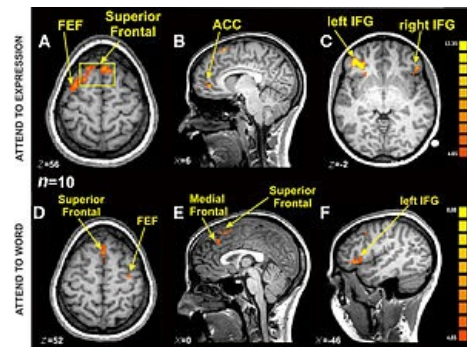
- Magnetic dipole
- Lorentz force
- Induced currents
- Magnetic resonance
- Fleming's left hand rule

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fMRI BOLD activation from Incongruent blocks compared with Congruent blocks in the Expression and Word instruction conditions