

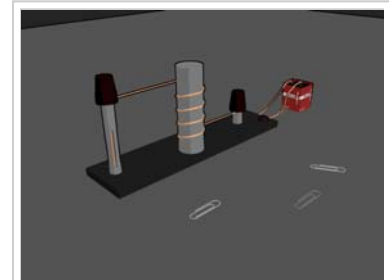
Electromagnet

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An **electromagnet** is a type of magnet in which the magnetic field is produced by the flow of electric current. The magnetic field disappears when the current ceases.

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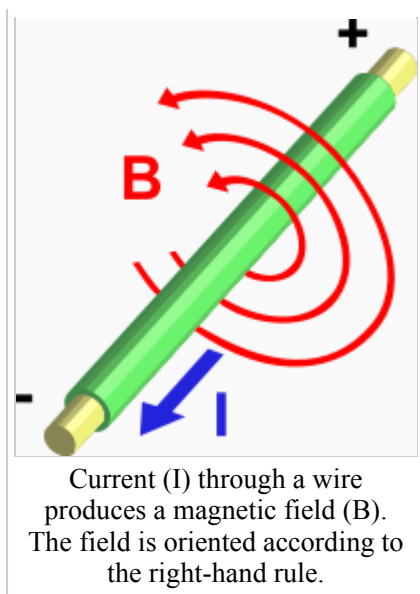


Electromagnet attracts paper clips when current is applied creating a magnetic field, loses them when current and magnetic field are removed

Introduction

A wire with an electric current passing through it, generates a magnetic field around it, this is a simple electromagnet. The strength of magnetic field generated is proportional to the amount of current.

In order to concentrate the magnetic field generated by a wire, it is commonly wound into a coil, where many turns of wire sit side by side. The magnetic field of all the turns of wire passes through the center of the coil. A coil forming the shape of a straight tube, a helix (similar to a corkscrew) is called a solenoid; a solenoid that is bent into a donut shape so that the ends meet is a toroid. Much stronger magnetic fields can be produced if a "core" of ferromagnetic material, such as soft iron, is placed inside the coil. The ferromagnetic core magnifies the magnetic field to thousands of times the strength of the field of the coil alone, due to the high magnetic permeability μ of the ferromagnetic material. This is called a ferromagnetic-core or iron-core electromagnet.

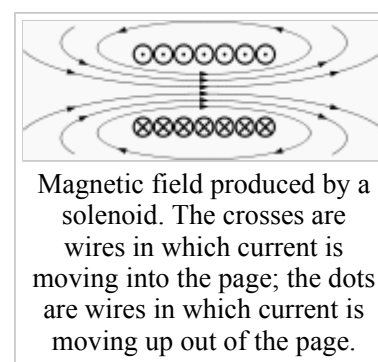


The direction of the magnetic field through a coil of wire can be found from a form of the right-hand rule.^{[1][2][3][4][5][6]} If the fingers of the right hand are curled around the coil in the direction of current flow (conventional current, flow of positive charge) through the windings, the thumb points in the direction of the field inside the coil. The side of the magnet that the field lines emerge from is defined to be the *north pole*.

The main advantage of an electromagnet over a permanent magnet is that the magnetic field can be rapidly manipulated over a wide range by controlling the amount of electric current. However, a continuous supply of electrical energy is required to maintain the field.

How electromagnets work

The material of the core of the magnet (usually iron) is composed of small regions called magnetic domains that act like tiny magnets (see ferromagnetism). Before the current in the electromagnet is turned on, the domains in the iron core point in random directions, so their tiny magnetic fields cancel each other out, and the iron has no large scale magnetic field. When a current is passed through the wire wrapped around the iron, its magnetic field penetrates the iron, and causes the domains to turn, aligning parallel to the magnetic field, so their tiny magnetic fields add to the wire's field, creating a large magnetic field that extends into the space around the magnet. The larger the current passed through the wire coil, the more the domains align, and the stronger the magnetic field is. Finally all the domains are lined up, and further increases in current only cause slight increases in the magnetic field: this phenomenon is called saturation.



When the current in the coil is turned off, most of the domains lose alignment and return to a random state and the field disappears. However in some materials some of the alignment persists, because the domains have difficulty turning their direction of magnetization, leaving the core a weak permanent magnet. This phenomenon is called hysteresis and the remaining magnetic field is called remanent magnetism. The residual magnetization of the core can be removed by degaussing.

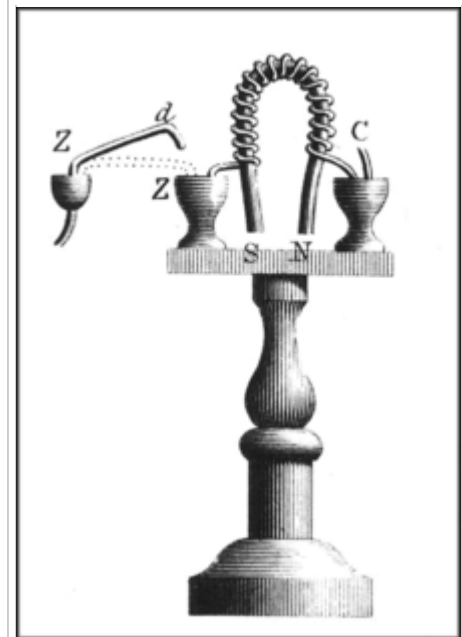
History

Danish scientist Hans Christian Ørsted discovered in 1820 that electric currents create magnetic fields. British scientist William Sturgeon invented the electromagnet in 1823.^{[7][8]} His first electromagnet was a horseshoe-shaped piece of iron that was wrapped with about 18 turns of bare copper wire (insulated wire didn't exist yet). The iron was varnished to insulate it from the windings. When a current was passed through the coil, the iron became magnetized and when the current was stopped, it was de-magnetized. Sturgeon displayed its power by showing that although it only weighed seven ounces (roughly 200 grams), it could lift nine pounds (roughly 4 kilos) when the current of a single-cell battery was applied. However, Sturgeon's magnets were weak because the uninsulated wire he used could only be wrapped in a single spaced out layer around the core, limiting the number of

turns. Beginning in 1827, US scientist Joseph Henry systematically improved and popularized the electromagnet.^[9] By using wire insulated by silk thread he was able to wind multiple layers of wire on cores, creating powerful magnets with thousands of turns of wire, including one that could support 2063 pounds. The first major use for electromagnets was in telegraph sounders.

Analysis of ferromagnetic electromagnets

For definitions of the variables below, see box at end of article.



Sturgeon's electromagnet, 1823

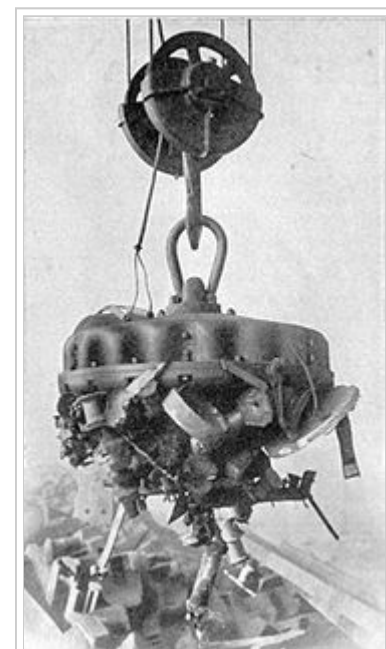
The magnetic field of electromagnets in the general case is given by Ampere's Law:

$$\int \mathbf{J} \cdot d\mathbf{A} = \oint \mathbf{H} \cdot d\mathbf{l}$$

which says that the integral of the magnetizing field \mathbf{H} around any closed loop of the field is equal to the sum of the current flowing through the loop. Another equation used, that gives the magnetic field due to each small segment of current, is the Biot-Savart law. Computing the magnetic field and force exerted by ferromagnetic materials is difficult for two reasons. First, because the geometry of the field is complicated, particularly outside the core and in air gaps, where *fringing fields* and *leakage flux* must be considered. Second, because the magnetic field \mathbf{B} and force are nonlinear functions of the current, depending on the nonlinear relation between \mathbf{B} and \mathbf{H} for the particular core material used. For precise calculations the finite element method is used.

Magnetic circuit - the constant \mathbf{B} field approximation

However, for a typical DC electromagnet in which the magnetic field path is confined to a single loop or circuit most of which is in core material, a simplification can be made. A common simplifying assumption, which will be used in this section, is that the magnetic field strength \mathbf{B} is constant around the magnetic circuit. Most of the magnetic field will be concentrated in the core material. Within the core the magnetic field will be approximately uniform across any cross section, so if in addition the core has roughly constant area throughout its length, the field in the core will be constant. This just leaves the air gaps, if any, between core sections. In the gaps the magnetic



Industrial electromagnet lifting scrap iron, 1914

field lines are no longer confined by the core, so they 'bulge' out beyond the outlines of the core before curving back to enter the next piece of core material, reducing the field strength in the gap. The bulges are called *fringing fields*. However, as long as the length of the gap is smaller than the cross section dimensions of the core, the field in the gap will be approximately the same as in the core. In addition, if parts of the core are too near other parts, some of the magnetic field lines will take 'short cuts' and not pass through the entire core circuit. This also occurs in the field near the windings, if the windings are not wrapped tightly around the core. This is called *leakage flux*. It also results in a lower magnetic field in the core. Therefore the equations in this section are valid for electromagnets for which:

1. the magnetic circuit is a single loop.
2. the core has roughly the same cross sectional area throughout its length.
3. the air gaps between sections of core material are not large compared with the cross sectional dimensions of the core.
4. there is negligible leakage flux

The main nonlinear feature of ferromagnetic materials is that the B field saturates at a certain value, which is around 1.6 teslas (T) for most high permeability core steels. The B field increases quickly with increasing current up to that value, but above that value the field levels off and increases at the much smaller paramagnetic value, regardless of how much current is sent through the windings. So the strength of the magnetic field possible from an iron core electromagnet is limited to 1.6-2 T.

Magnetic field created by a current

The magnetic field created by an electromagnet is proportional to both the number of turns in the winding, N , and the current in the wire, I , hence this product, NI , in ampere-turns, is given the name magnetomotive force. For an electromagnet with a single magnetic circuit, of which length L_{core} is in the core material and length L_{gap} is in air gaps, Ampere's Law reduces to:^{[10][11]}

$$NI = H_{\text{core}}L_{\text{core}} + H_{\text{gap}}L_{\text{gap}}$$

$$NI = B \left(\frac{L_{\text{core}}}{\mu} + \frac{L_{\text{gap}}}{\mu_0} \right) \quad (1)$$

where $\mu = B/H$
 $\mu_0 = 4\pi(10^{-7}) \text{ N} \cdot \text{A}^{-2}$ is the permeability of free space (or air).

This is a nonlinear equation, because the permeability of the core, μ , is a function of the magnetic field. For an exact solution, the value of μ at the B value used must be obtained from the core material hysteresis curve. If B is unknown, the equation must be solved by numerical methods. However, if the magnetomotive force is well above saturation, so the core material is in saturation, the magnetic field won't vary much with changes in NI anyway. For a closed magnetic circuit (no air gap) most core materials saturate at a magnetomotive force of roughly 800 ampere-turns per meter of flux path.

For most core materials, $\mu_r = \mu/\mu_0 \approx 2000 - 6000$.^[11] So in equation (1) above, the second term dominates. Therefore, in magnetic circuits with an air gap, the behavior of the magnet depends strongly on the length of the air gap, and the length of the flux path in the core doesn't matter much.

Force exerted by magnetic field

When none of the magnetic field bypasses any sections of the core (no flux leakage), the force exerted by an electromagnet on the core material is:

$$F = \frac{B^2 A}{2\mu_0} \quad (2)$$

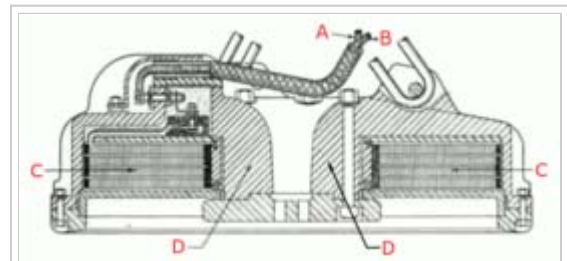
The 1.6 T limit on the field mentioned above sets a limit on the maximum force per unit core area, or pressure, an iron-core electromagnet can exert; roughly:

$$\frac{F}{A} \approx 1000 \text{ kPa} = 10^6 \text{ N/m}^2 = 145 \text{ lbf} \cdot \text{in}^{-2}$$

Given a core geometry, the B field needed for a given force can be calculated from (2); if it comes out to much more than 1.6 T, a larger core must be used.

Closed magnetic circuit

For a closed magnetic circuit (no air gap), such as would be found in an electromagnet lifting a piece of iron, equation (1) becomes:



Cross section of lifting electromagnet like that in above photo, showing cylindrical construction. The windings (C) are flat copper strips to withstand the Lorentz force of the magnetic field. The core is formed by the thick iron housing (D) that wraps around the windings.

$$B = \frac{NI\mu}{L} \quad (3)$$

Substituting into (2), the force is:

$$F = \frac{\mu^2 N^2 I^2 A}{2\mu_0 L^2} \quad (4)$$

It can be seen that to maximize the force, a core with a short flux path and a wide cross sectional area is preferred. To achieve this, in applications like lifting magnets (see photo above) and loudspeakers a flat cylindrical design is often used. The winding is wrapped around a short wide cylindrical core that forms one pole, and a thick metal housing that wraps around the outside of the windings forms the other part of the magnetic circuit, bringing the magnetic field to the front to form the other pole.

Force between electromagnets

The above methods are inapplicable when most of the magnetic field path is outside the core. For electromagnets (or permanent magnets) with well defined 'poles' where the field lines emerge from the core, the force between two electromagnets can be found using the 'Gilbert model' which assumes the magnetic field is produced by fictitious 'magnetic charges' on the surface of the poles, with pole strength m and units of Ampere-turn meter. Magnetic pole strength of electromagnets can be found from:

The force between two poles is:

This model doesn't give the correct magnetic field inside the core, and thus gives incorrect results if the pole of one magnet gets too close to another magnet.

Side effects in large electromagnets

There are several side effects which become important in large electromagnets and must be provided for in their design:

Ohmic heating

The only power consumed in a DC electromagnet is due to the resistance of the windings, and is dissipated as heat. Some large electromagnets require cooling water circulating through pipes in the windings to carry off the waste heat.

Since the magnetic field is proportional to the product NI , the number of turns in the windings N and the current I can be chosen to minimize heat losses, as long as their product is constant. Since the power dissipation, $P = I^2R$, increases with the square of the current, the power lost in the windings can be minimized by reducing I and increasing the number of turns N proportionally. For this reason most electromagnets have windings with many turns of wire.

However, the limit to increasing N is that the larger number of windings takes up more room between the magnet's core pieces. If the area available for the windings is filled up, more turns require going to a smaller diameter of wire, which has higher resistance, which cancels the advantage of using more turns. So in large magnets there is a minimum amount of heat loss that can't be reduced. This increases with the square of the magnetic flux B^2 .

Inductive voltage spikes

An electromagnet is a large inductor, and resists changes in the current through it's windings. Any sudden changes in the winding current cause large voltage spikes across the windings. This is because when the magnet is turned on energy from the circuit must be stored in the magnetic field, and when it is turned off the energy in the field is returned to the circuit.

If an ordinary switch is used to control the winding current, this can cause sparks at the terminals of the switch. This doesn't occur when the magnet is switched on, because the voltage is limited to the power supply voltage. But when it is switched off, the energy in the magnetic field is suddenly returned to the circuit, causing a large voltage spike and an arc across the switch contacts, which can damage them.

With small electromagnets a capacitor is often used across the contacts, which reduces arcing by temporarily storing the current, allowing the current through the electromagnet to change more slowly. Large electromagnets are usually powered by variable current electronic power supplies, controlled by a microprocessor, which prevent voltage spikes by accomplishing current changes in gentle ramps. It may take several minutes to energize or deenergize a large magnet.

Lorentz forces

In powerful electromagnets, the magnetic field exerts a force on each turn of the windings, due to the Lorentz force $q\mathbf{v} \times \mathbf{B}$ acting on the moving charges within the wire. The Lorentz force is perpendicular to both the axis of the wire and the magnetic field. It can be visualized as a pressure between the magnetic field lines, pushing them apart. It has two effects on an electromagnet's windings:

- The field lines within the axis of the coil exert a radial force on each turn of the windings, tending to push them outward in all directions. This causes a tensile stress in the wire.
- The leakage field lines between each turn of the coil exert a repulsive force between adjacent turns, tending to push them apart.

The Lorentz forces increase with B^2 . In large electromagnets the windings must be firmly clamped in place, to prevent motion on power-up and power-down from causing metal fatigue. In the Bitter design, below, used in very high field research magnets, the windings are constructed as flat disks to resist the radial forces, and clamped in an axial direction to resist the axial ones.

Core losses

In alternating current (AC) electromagnets, used in transformers, inductors, and AC motors and generators, the magnetic field is constantly changing. This causes energy losses in their magnetic cores that are dissipated as heat in the core. The losses stem from two processes:

- *Eddy currents*: From Faraday's law of induction, the changing magnetic field induces circulating electric currents inside nearby conductors, called eddy currents. The energy in these currents is dissipated as heat in the electrical resistance of the conductor, so they are a cause of energy loss. Since the magnet's iron core is conductive, and most of the magnetic field is concentrated there, eddy currents in the core are the major problem. Eddy currents are closed loops of current that flow in planes perpendicular to the magnetic field. The energy dissipated is proportional to the area enclosed by the loop. To prevent them, the cores of AC electromagnets are made of stacks of thin steel sheets, or laminations, oriented parallel to the magnetic field, with an insulating coating on the surface. The insulation layers prevent eddy current from flowing between the sheets. Any remaining eddy currents must flow within the cross section of each individual lamination, which reduces losses greatly. Another alternative is to use a ferrite core, which is a nonconductor.
- *Hysteresis losses*: Reversing the direction of magnetization of the magnetic domains in the core material each cycle causes energy loss, because of the coercivity of the material. These losses are called hysteresis. The energy lost per cycle is proportional to the area of the hysteresis loop in the BH graph. To minimize this loss, magnetic cores used in transformers and other AC electromagnets are made of "soft" low coercivity materials, such as silicon steel or soft ferrite.

The energy loss per cycle of the AC current is constant for each of these processes, so the power loss increases linearly with frequency.

High field electromagnets

Superconducting electromagnets

Main article: Superconducting magnet

When a magnetic field higher than the ferromagnetic limit of 1.6 T is needed, superconducting electromagnets can be used. Instead of using ferromagnetic materials, these use superconducting windings cooled with liquid helium, which conduct current without electrical resistance. These allow enormous currents to flow, which generate intense magnetic fields. Superconducting magnets are limited by the field strength at which the winding material ceases to be superconducting. Current designs are limited to 10–20 T, with the current (2009) record of 33.8 T.^[12] The necessary refrigeration equipment and cryostat make them much more expensive than ordinary electromagnets. However, in high power applications this can be offset by lower operating costs, since after startup no power is required for the windings, since no energy is lost to ohmic heating. They are used in particle accelerators, MRI machines, and research.

Bitter electromagnets

Main article: Bitter electromagnet

Since both iron-core and superconducting electromagnets have limits to the field they can produce, the highest manmade magnetic fields have been generated by air-core nonsuperconducting electromagnets of a design invented by Francis Bitter in 1933, called Bitter electromagnets.^[13] These consist of a solenoid made of a stack of conducting disks, arranged so that the current moves in a helical path through them. This design has the mechanical strength to withstand the extreme Lorentz forces of the field, which increase with B^2 . The disks are pierced with holes through which cooling water passes to carry away the heat caused by the high current. The highest continuous field achieved with a resistive magnet is currently (2008) 35 T.^[12] The highest continuous magnetic field, 45 T,^[13] was achieved with a hybrid device consisting of a Bitter magnet inside a superconducting magnet.

Exploding electromagnets

The factor limiting the strength of electromagnets is the inability to dissipate the enormous waste heat, so higher fields, up to 90 T,^[12] have been obtained from resistive magnets by pulsing them. The highest magnetic fields of all have been created by detonating explosives around a pulsed electromagnet as it is turned on. The implosion compresses the magnetic field to values of around 1000 T^[13] for a few microseconds.

Uses of electromagnets

Electromagnets are widely used in many electric devices, including:

- Motors and generators
- Relays, including reed relays originally used in telephone exchanges
- Electric bells
- Loudspeakers
- Magnetic recording and data storage equipment: tape recorders, VCRs, hard disks

- Particle accelerators
- Magnetic locks
- Magnetic separation of materials
- Industrial lifting magnets
- Electromagnetic suspension used for MAGLEV trains

Definition of terms

A	square meter	cross section area of core
B	tesla	Magnetic field
F	newton	Force exerted by magnetic field
H	ampere per meter	Magnetizing field
I	ampere	Current in the winding wire
L	meter	Total length of the magnetic field path $L_{\text{core}} + L_{\text{gap}}$
L_{core}	meter	Length of the magnetic field path in the core material
L_{gap}	meter	Length of the magnetic field path air gap
m_1, m_2	ampere meter	Pole strength of the electromagnets
μ	newton per square ampere	Permeability of the electromagnet core material
μ_0	newton per square ampere	Permeability of free space (or air) = $4\pi(10^{-7})$
μ_r	-	Relative permeability of the electromagnet core material
N	-	Number of turns of wire on the electromagnet
r	meter	Distance between the poles of two electromagnets

See also

- Dipole magnet - Electromagnet used in particle accelerators
- Electromagnetism
- Magnetic bearing
- Quadrupole magnet - Electromagnet used in particle accelerators
- Superconducting magnet - Electromagnet that uses superconducting windings
- Bitter electromagnet - a powerful type of electromagnet

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External links

- Magnets from Mini to Mighty: Primer on electromagnets and other magnets (<http://www.magnet.fsu.edu/education/tutorials/magnetacademy/magnets/>) National High Magnetic Field Laboratory
- Magnetic Fields and Forces (<http://instruct.tri-c.edu/fgram/web/mdipole.htm>) Cuyahoga Community College
- Fundamental Relationships (http://geophysics.ou.edu/solid_earth/notes/mag_basic/mag_basic.html) School of Geology and Geophysics, University of Oklahoma

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Categories: Fundamental physics concepts | Electromagnetism | Types of magnets

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