Magnetism

Types of Magnetic Materials Magnetic substances can be classified into three basic groups, according to their response to a magnet. Note the strength and direction of the interaction.
a) Ferromagnetic materials are strongly attracted to magnets
b) Paramagnetic materials are weakly attracted to magnets
c) Diamagnetic materials are weakly repelled by magnets.

Causes of Magnetic Behavior Magnetic properties are thought to result from two types of electron motions within atoms. Electrons orbiting nuclei (like the year long motion of the earth around the sun) cause diamagnetism. Electrons also revolve around their own axes (like the 24 hr motion of the earth around its N – S axis.) The interaction between the two types of motions is thought to cause permanent magnetism.

Magnetic Poles A bar magnet suspended by a thread so that it can twist freely aligns itself with the earth's magnetic field. The end of the magnet (sometimes colored red) that points to the Arctic is called the N – seeking pole; it is actually the S pole of the magnet. The end of the magnet that points to the Antarctic is called the S – seeking pole; it is really the N pole of the magnet. Just as with electric charges, opposite poles attract and like ones repel.

Induced Magnetism Iron contains microscopic areas called domains. Each domain behaves like a miniature bar magnet, all at different angles to each other. If he iron becomes magnetized, most of the domains line up parallel to each other. If any material is heated to its Curie Temperature, the thermal energy causes its particles to jostle about so much the domains will never stay lined up and magnetization is impossible. A permeable material is one in which the domains line up readily and saturation occurs when an external magnetic field has caused most of the domains to line up.

Soft iron is a metal that shows induced magnetism – it becomes a temporary magnet when placed next to a magnet because its domains are caused to line up. It gradually loses its induced magnetic properties when taken away from the magnet as the domains lose their common orientation. In contrast, steel would retain its induced magnetism for a long time and is therefore used to make permanent magnets; its domains remain lined up for an extended period of time.

Magnetic Force Fields The shape and behavior of these fields is similar to electric fields.

Electromagnetism Hans Oerstead (Danish, 1819) noticed that current flowing through a wire caused the needle of a nearby compass to swing away from its N– S alignment. His demonstration was a key part of the investigation into the connections between electricity and magnetism.

Some of the basic ideas in electromagnetism are summarized in the four Left Hand Rules. These rules describe how part's of one's left hand can help one remember the relationships between: conductor shape, current direction, and the shapes and directions of the magnetic fields.

First Left Hand Rule

Situation: current flowing through a straight wire creates a cylindrical magnetic force field around the wire.

The Rule: place thumb on wire in direction of current; fingers wrapped around the wire show the shape of the field; the fingertips point in the direction of the force field. Since the field is a cylinder, there is no one place that is N. Nonetheless, a compass needle will align itself parallel to the force lines, with its N – seeking pole pointing in the opposite direction to your fingertips.

Calculations: $B = \frac{k\,I}{D}$ Magnetic flux is the imaginary flow of magnetic force through a magnetic force field. This equation describes how the density of magnetic flux (the strength of the magnetic force field) changes with distance out from the wire.

B = the magnetic field's strength (its magnetic induction or magnetic flux density) at some point out away from the wire, measured in Tesla's (T) or Webers / m^2.
k = a constant, $2 * 10^{-7}$ N/amp^2
I = current in wire, in A
D = distance out from the wire to a selected spot, in m

Q. Find the magnetic induction at a point 1 m out from a straight wire carrying 5 A of current.

$$B = \frac{2 * 10^{-7}\ \text{N/amp}^2 * 5\ \text{A}}{1\ \text{m}} = 1 * 10^{-6}\ \text{T}$$

Second Left Hand Rule

Situation: current flowing through a coil creates an invisible bar magnet within the coil's core.
The Rule: wrap fingers around coil, fingertips tracing the direction of current flow through the loops; the thumb extended along the axis of the coil points to the magnet's N – seeking pole.

Calculations: $B = \frac{k \pi I}{r}$ This equation relates the magnetic induction at the center of a loop to the radius of the loop.

B = the magnetic flux density at the center of a loop, in T or Webers / m^2
k = as before
I = current running through loops of the coil, in A
r = the radius of the coil's loops, in m

Q. Find the magnetic induction at the center of a coil, radius = 0.16 m, and carrying 4 A of current.

$$B = \frac{2 * 10^{-7}\ \mathrm{N/amp^2} * \pi * 4\ \mathrm{A}}{0.16\ \mathrm{A}} = 1.57 * 10^{-5}\ \mathrm{T}$$

Applications: Electromagnets These are a direct tie-in with electrified coils. A piece of soft iron placed within the coil's core concentrates the magnetic force lines and so creates a stronger magnet. The soft iron has a high magnetic permeability which allows it to concentrate magnetic force lines and thereby magnify magnetic strength. An electromagnet's strength is related to: the amount of current in the coil, the number of loops (turns) in the coil, and the permeability of the metal in its core.

Third Left Hand Rule

Situation: an electrified straight wire placed in a magnetic field in a gap between opposite poles will react to it by moving. The wire creates an invisible magnet which behaves just like a solid magnet placed next to another magnet – it is attracted or repelled.

The Rule: hand flat, fingers pointing across the gap toward S; the thumb lies on the wire in the direction of current flow; the palm shows the direction in which the wire will move.

Calculations: $F = B\,I\,L$ This equation describes the force exerted on the wire by the magnetic field in the gap between the two magnet poles.

F = the push or pull felt by the wire, in N
B = the magnetic flux density in the gap between the magnet poles, in T or Webers / m^2
I = current carried in wire, in A
L = the length of the wire in the gap, in m

Q. Find the force exerted on a 0.2 m long wire carrying 20 A of current when it is in a 0.4 T magnetic field.

$$F = 0.4\ \mathrm{T} * 20\ \mathrm{A} * 0.2\ \mathrm{m} = 1.6\ \mathrm{N}.$$

Variations: Interacting Wires A related situation is the interaction of two parallel electrified wires. Each creates an its own invisible magnet and the two interact just like two solid magnets, attracting or repelling each other. **Note:** When the currents in the two wires are parallel, the wires attract. Currents flowing in opposite directions along the wires cause repulsion. Diagrams from the First Left Hand Rule help us see why.

Calculations: $F = \frac{k I_1 I_2 L}{d}$

F = force of interaction between the two electrified wires, in N
k = as above
I_1, I_2 = the currents in the two wires, in A
L = the common straight length of the two wires, in m
d = the distance between the wires, in m

Q. Find the interactive force between two parallel wires, one carrying 1 A, the other 2 A, if their common straight length is 1 m and they lie 0.1 m apart. If the currents are parallel, what is the direction of the interaction?

$$F = \frac{2 * 10^{-7}\ \text{N/amp}^2 * 1\ \text{A} * 2\ \text{A} * 1\ \text{m}}{0.1\ \text{m}} = 4 * 10^{-6}\ \text{N}$$, attraction.

Applications: Electric motors These are a direct off shoot of the Third Left Hand Rule. A single straight wire in a magnetic field will move in just one direction. If this linear motion can become rotational, an electric motor is the result. If the straight wire is shaped like a fly swatter or loop it becomes an armature. The current flows up one side, across the end and down the other side. The current flowing in opposite directions along the two sides of the armature causes an upward motion on one side and a downward motion on the other – the result is rotation.

Galvanometer A galvanometer is a sensitive DC meter that is basically an electric motor with a limited amount of rotation. A spring attached to the armature creates a back force to counterbalance the rotational force created by current flowing through the armature. A pointer attached to the back end of the armature moves across a faceplate with appropriate quantities. Should the spring not be strong enough to prevent over– rotation, a small pin at either end of the scale prevents the pointer (and the armature) from rotating out of sight. The placement and size of a protective resistor inside the galvanometer case allows it to be used as either an ammeter or a voltmeter.

Ammeter An ammeter is hooked up in series to a circuit so that all the current will have to pass through it. Inside the ammeter's case however, a small resistor is hooked up in parallel to allow most of the current to bypass the delicate galvanometer. By knowing how much current is diverted through the small resistor, appropriately large values can be placed on the meter's scale.

Q. A galvanometer has an armature resistance of 4 Ω and can tolerate a voltage of 8 mV. A protective resistor of what size will allow it to read up to 7.5 A?

a) the first step is to find the tiny amount of current that can safely pass through the galvanometer:
$I_G = V_G / R_G = 0.008 \text{ V} / 4\ \Omega = 0.002 \text{ A}$

b) the second step is to find how much current must be diverted through the protective resistor.
Because of the parallel setup inside the ammeter's case, the $I_T = I_R + I_G$ and so:
$I_T = I_R + I_G$ or $I_R = I_T - I_G = 7.5 \text{ A} - 0.002 \text{ A} = 7.498 \text{ A}$

c) the last step is to find the rating of the protective resistor. Also because of the parallel setup inside the voltmeter's case, the $V_G = V_R$. And so:
$R_R = V_R / I_R = 0.008 \text{ V} / 7.498 \text{ A} = 0.00107\ \Omega$

Voltmeter

A voltmeter can be hooked up in parallel to a circuit because, although it creates a new branch, the voltage is the same in all branches. Unlike an ammeter which must have all the current flowing through it to measure the number of electrons in motion, a voltmeter works by holding back the current and measuring the electrical pressure, the voltage. Inside its case, a large resistor is hooked up in series to the sensitive galvanometer to keep most of the current from entering it. By knowing how much current has been held back, appropriately large values can be printed on the scale.

Q. A galvanometer has an armature resistance of 90 Ω and can tolerate a current of 90 mA. A protective resistor of what size will allow it to function as a 300 V voltmeter?

a) the first step is to find the maximum voltage that can be tolerated by the galvanometer:
$V_G = I_G R_G = 0.09 \text{ A} * 90\ \Omega = 8.1 \text{ V}$

b) the second step is to find what voltage must be tolerated by the protective resistor. Because of the series set up inside the voltmeter's case, the $V_T = V_R + V_G$ and so:
$V_R = V_T - V_G = 300 \text{ V} - 8.1 \text{ V} = 291.9 \text{ V}$

c) the last step is to find the rating of the protective resistor. Also because of the series setup inside the voltmeter's case, $I_G = I_R$ and so:
$R_R = V_R / I_R = 291.9 \text{ V} / 0.09 \text{ A} = 3243\ \Omega$

Fourth Left Hand Rule

Situation: a wire moved through the magnetic field in the gap between opposite poles releases current. The process of getting current from wires moving through magnetic fields is electromagnetic induction. Michael Faraday discovered the process in 1821.

The Rule: hand flat, fingers point to S across the gap; thumb points in direction in which wire is moved; palm shows direction in which current flows through the wire.

Calculations: EMF = V B L This equation describes the factors affecting the amount of potential difference is created in the moving wire.

EMF = the electromotive force created in the moving wire by electromagnetic induction, in V
V = the velocity of the wire through the magnetic field, in m/s
B = the magnetic flux density, in T or Webers / m^2
L = the length of the wire exposed to the magnetic field, in m

Q. Find the potential difference in a 0.4 m wire moving at 5 m/s through a $2 * 10^{-2}$ T magnetic flux.

$\text{EMF} = 5 \text{ m/s} * 2 * 10^{-2} \text{ T} * 0.4 \text{ m} = 0.04 \text{ V}$

Paradox: Lenz's Law The ironic thing about the Fourth Left Hand Rule is that it tries to stop itself from happening! This Rule tells us that, as soon as the wire bathed in the magnetic field between the magnet's jaws is caused to move, current begins to flow from it. The LHR 1 tells us the wire immediately uses this "induced" current to create a magnetic field around itself – no surprise. But, the direction in which the induced current flows in the wire causes its magnetic force field to be opposite in polarity to that of the field between the magnet's jaws. Since the polarity of the two fields are opposite, they grab at each other: the large magnet tries to keep the small magnet (the wire) from moving. And, if the wire does not move, it releases no current. This idea is called Lenz's Law.

Applications: Transformers This device is a combination of the 2nd and 4th Left Hand Rules. It is just a metal donut with insulated wire wrapped around opposite sides. Its main function is to change AC voltage and as a consequence it also changes the current, but in the reverse fashion. Current flowing through the primary coils creates a magnetic field, as in the 2nd Left Hand Rule. The metal concentrates and channels the field and as the force lines flow through the center of the secondary coils, the 4th Left Hand Rule generates current in these coils.

Q. A transformer has 150 primary and 3 000 secondary coil turns. If 110 V are applied to the primary side and the secondary current is 0.1 A, find: secondary voltage, primary current, input power, output power, and efficiency.

a) secondary voltage

$$\frac{V_S}{V_P} = \frac{N_S}{N_P} \quad \text{or} \quad V_S = \frac{N_S * V_P}{N_P} = \frac{3\,000 * 110\text{ V}}{150} = 2\,200\text{ V.}$$

b) primary current

$$\frac{I_S}{I_P} = \frac{N_P}{N_S} \quad \text{or} \quad I_P = \frac{I_S * N_S}{N_P} = \frac{0.1\text{ A} * 3\,000}{150} = 2\text{ A.}$$

c) input power

$$P_{IN} = I_P\, V_P = 2\text{ A} * 100\text{ V} = 220\text{ W.}$$

d) output power

$$P_{OUT} = I_S\, V_S = 0.1\text{ A} * 2\,200\text{ V} = 220\text{ W.}$$

e) efficiency

$$\text{Eff} = \frac{P_{OUT}}{P_{IN}} = \frac{220\text{ W}}{220\text{ W}} = 100\%$$

Note: in reality, the efficiency is always less than 100% because some energy is lost as heat and perhaps a bit of electrical buzz.

Power ratings Power is a measure of the rate at which energy (electrical in this case) is transferred. Its unit is the Watt or W. A kilowatt = 1000 W. A kilowatt hour = the number of watts * the number of hours of energy use. A kilowatt hour also = 1000 W * 3600 s = $3.6 * 10^{6}$ Joules or 3.6 M J.

Transformer History: Their Role as Safety Devices Many electrical devices used to have metal cases and if the internal wiring became frayed, current might leak onto the metal case. When you touched it, there was a danger of serious shock because the leaked current, trying to complete the circuit, might use you as a path to try to reach "ground", i.e., to get back to the wall socket or actually into the Earth! Transformers reduced this hazard because the current from a transformer starts in the transformer and has no impulse to reach the wall socket or the Earth. So, if your hand touched a bare wire coming from the transformer, the current would tend not go through you since this was not a path back to its source, the transformer. The current might enter your hand and create a tingle but it would not travel down through your body and out your legs, causing major shock damage. This is sort of like a bird perched on a wire – it gets no shock because its body is not a route for the electricity trying to get to ground and also because the bird's body is a less favorable path for the electricity to flow through than just along the wire itself. Today, nearly everything has a plastic case so the shock hazard is reduced to start with. So, why are transformers still so common? To allow manufacturers to use circuits requiring any voltage they find convenient – the transformer can change the line voltage of 110 V into whatever is called for.