Understanding Magnetism

Introduction

There is something almost magical about magnets! It is the fact that as babies, children and even adults, we can get hold of them and play with them. They appeal to our deepest human instinct, yet they are unlike anything else in our experience because they exert forces on each other and many metal objects without any visible means of doing so.

It is important to understand that magnets are manufactured artefacts and that as such they owe their behaviour more to the skill of the manufacture than to raw physics. Modern toys which contain magnets can show little respect for the idea that a magnet has a north pole and a south pole. Perhaps that is a good thing because north and south poles are man made properties of magnets.

Magnetism, in the ordinary sense of the word, is a freak of nature. It should not happen and 96% of the elements show no appreciable magnetic properties. Only iron, cobalt, nickel and gadolinium possess this property. The correct scientific name is ferromagnetism named after iron. It is not a very stable property in the sense that it can be disrupted by thermal vibration at temperatures ranging from room temperature for gadolinium (16°C) to red heat for iron (770°C) and cobalt (1131°C). These are called the Curie temperatures.

Two other much weaker magnetic effects have been detected called paramagnetism and diamagnetism, but the forces generated are quite insignificant. None of the observed magnetic effects give any hint as to the true nature and purpose of magnetic fields. Atoms consist of a lot of empty space filled by orbiting electrons. Each electron is surrounded by an intense magnetic field generated by its motion. In addition, magnetic flux is quantised and each orbit is wrapped with an integer number of quanta of magnetic flux. Modern Physics abandoned this understanding of how nature works in the early part of the twentieth century. In presenting our unified theory, we seek to correct this error.

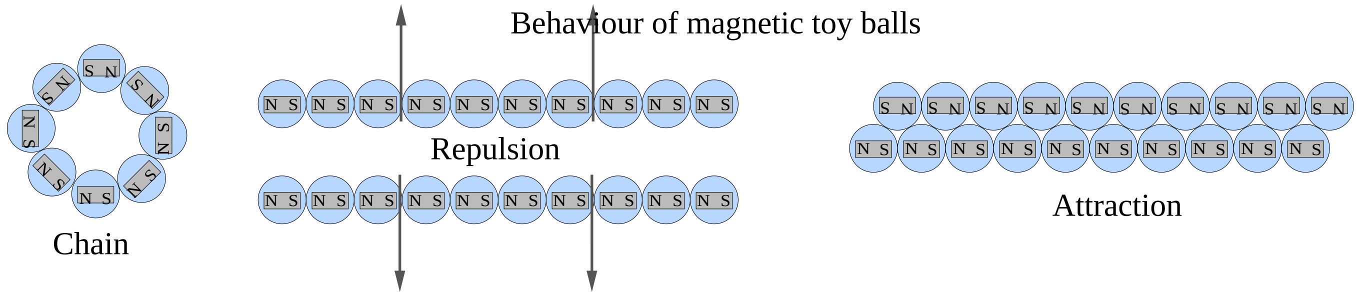
Ferromagnetism

The basic property of magnetism comes from the fact that electrons within an atom orbit the nucleus and form what we call a current loop. Their action generates a magnetic field. A hydrogen atom with its single electron is like a tiny magnet but unlike magnets, hydrogen atoms like to join together in pairs so that their magnetism cancels each other out and hydrogen molecules are not magnetic. If an atom has an even number of electrons, their orbits will align so that their magnetic fields cancel out.

Metals are very special because of the way the atoms are stuck together. An individual metal atom has one or two electrons orbiting outside the main body of the atom. When metal atoms join to form a solid, these outer electrons become free to roam around inside the metal. In the cases of iron, cobalt, nickel and gadolinium, one electron orbit within the body of the atom is unpaired but there is nothing unusual about this. What is unusual about these four metals is the effect of a magnetic field on that unpaired orbiting electron.

For some reason to do with the way all the electron orbits of iron fit together, the effect of a background magnetic field is to cause a reduction in the energy content of the atom when aligned parallel to its unpaired electron orbit. The normal interaction is to increase the energy content, but iron, cobalt, nickel and gadolinium are unusual in this respect. Their energy content is decreased, so two neighbouring atoms will align parallel to one another releasing some energy which can contribute to the formation of a magnetic field. So as they cool below the Curie temperature, the electron orbits in adjacent atoms align with each other's magnetic fields. This still does not explain why these fore elements can be magnetised! There is a toy on the market consisting of plastic balls each containing a magnet. They readily form chains, but chains can only lie side by side if their magnets point the other way.

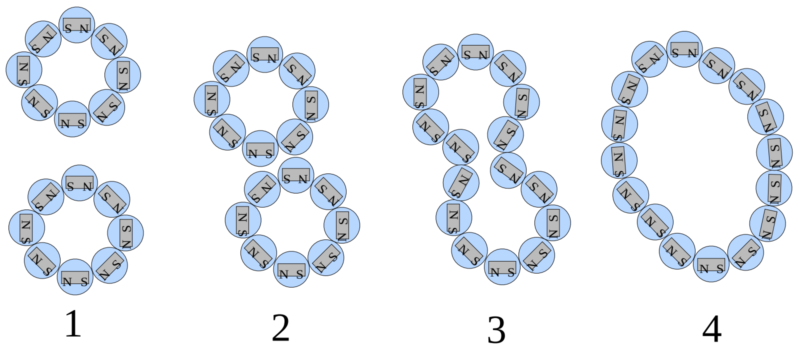
Behaviour of magnetic toy balls



Scientist discovered a long time ago that it was possible to see the magnetism of a piece of iron by cleaning the surface with acid and looking at it under a microscope. The iron appears divided into separate regions which we call domains. Each domain is a magnet. The domains are arranged to form closed loops of magnetic flux. The properties of a magnetic material depend on how easy it is for the the domain boundaries to move. Steel contains carbon and other impurities and these make it hard for the domain boundaries to move. A steel bar can be tuned into a magnet by aligning all its domains. Because of all the impurities, the domain boundaries are unable to move and the bar remains permanently magnetised. We say steel is a hard magnetic material. Pure iron is a soft magnetic material because the domain boundaries can return very easily to the demagnetised state. Actually, there is no such thing as pure iron because it is impossible to remove all the impurities, but some impurities actually make it easier for the domain boundaries to move producing what we call soft iron. Metallurgists have put great effort developing both hard magnetic alloys and soft magnetic alloys. It has even been possible to film the domain boundaries moving with changes in the magnetic field through a piece of soft iron.

Playing with the plastic magnetic balls gives us some insight into the way in which loops of magnetic flux behave. If two loops are pushed together, they break and rejoin with each other to form a bigger loop.

Chains join together



A relatively modern discovery is that fact that magnetic flux is quantised. It comes in strands which must form closed loops. Magnetic flux exists at two completely different scales. Within an atom, it can wrap around the orbit of an electron, but other than that, even within a domain, the cross section of a quantum stand of flux contains several thousand atoms. This sets a lower limit to the size of domains.

It is important to understand that the quantum nature of magnetic flux makes it impossible for the magnetic flux to conform to the local variations in the magnetic intensity. When we speak of the magnetic field of an atom, we mean its magnetic intensity. Only when we get billions of atoms together is it possible for magnetic flux to form a stable magnetic field.

As iron cools below its Curie temperature, the earth's magnetic field is already there for the atoms to align with. Every blacksmith knows the importance of the direction of earth's magnetic field relative the steel bar that is being forged. It is our contention that as iron cools below its Curie temperature, atoms initially line up with the earth's magnetic field, until regions can form which are large enough to contain a quantum strand of flux allowing domains to form. But flux comes in loops, and the aligned atoms within a domain create a magnetic intensity field which exists outside the domain and forms continuous loops, so other domains form in the opposite direction and still more form in other directions to allow the quantum strands of flux to form closed loops creating the domains structure of the un-magnetised iron.

The skill of the blacksmith lies in turning iron into steal through the adsorption of carbon and the formation of a grain structure though hammering. Long ago, they discovered that this also imparted magnetic properties and if a steel bar was placed in a north south direction during this process, it became a magnet. The terms hard and soft were taken form the mechanical properties applied to the magnetic properties of iron and steel. With the discovery of electromagnetism and the invention of the first motors and generators, much research was put into developing alloys which emphasised the two properties of hard and soft.

If you have any steel magnets, they will probably be made of Alnico. If you have any electronic equipment with a transformer, its core might well be made of an allow called supermalloy. More recently, there has been a considerable development in the use of chemical compounds. The aerial in your portable radio probably consists of coils wound around a ferrite rod. The transformers in all your PSUs will be also be made of ferrite. Your computer disc drives and maybe some modern electric motors will contain ceramic magnets.

The hysteresis curve

All magnetic fields are generated by electric currents. They may be real electric currents in wires, but in most cases, they are the currents which result from orbiting electrons. A magnetic field has two distinct properties; magnetic intensity and flux density. The magnetic intensity is represented by the letter *H* and describes the action of the electric currents and orbiting electrons. It is the sum of the actions of zillions of individual electrons. Magnetic flux is the substance of the magnetic field and is described by its flux density *B*.

The behaviour of ferromagnetic materials is best described by plotting the flux density *B* against the magnetic intensity *H*. The result is known as a hysteresis loop or hysteresis diagram. The principle is that a sample is cycled over a range of values of *H* which is quite easy to do with an oscilloscope and AC current to produce the result shown in (a) below. But the the actual shape of the curve depends on the starting point and the variation in *H*.

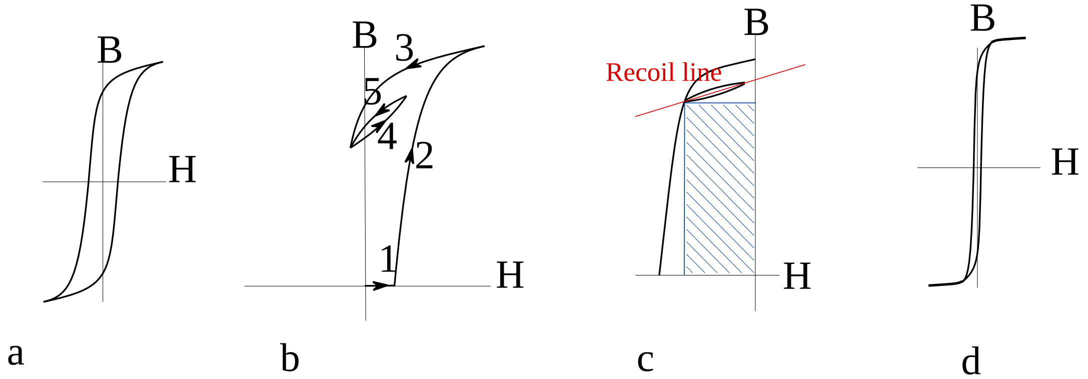


Fig (a) shows a typical hysteresis curve, fig (b) (at twice the scale) the sort of path which shows what happens to the magnetic field within a nail when it is picked up with a powerful magnet (1) and (2). The effect of removing the nail (3) takes it into the negative *H* region. If *H* is now increased, the curve now follows the minor loop (4) returning along (5) when H is removed.

The engineer seeks to create order from this chaos and produce designs where the behaviour approximates to a straight line on the graph. Fig. (c) shows the part of the hysteresis diagram called the "de-magnetisation curve" for a magnet in some application like a door catch. The minor loop is approximated to by a line called the "recoil line". Modern ceramic magnets have a very much flatter minor loop making the recoil line a much more accurate approximation.

The point where the recoil line meets the hysteresis curve is called the "operating point". The rectangle represents the product BH. The air gap between the poles of the magnet is designed to give the maximum energy density in the magnet when the keeper is removed and this is achieved by setting the operating point to give the maximum value of BH.

At the other extreme, alloys and ferrites developed for use in transformer cores have very narrow hysteresis loops as in (d). Assembly of a transformer's laminated core with resin to electrically insulate the laminates from each other and avoid eddy current loss gives a good approximation to linear behaviour. Under these conditions, we can define a property of the material called its permeability μ and write:

$$B = \mu H$$

Reversible demagnetization

Nails are made from mild steel which has a low carbon content. Its magnetic properties mirror its physical properties. It is neither hard nor soft. So when a nail is picked up with a magnet and then released, there is not enough resistance to the movement of domain boundaries to enable it to retain its magnetism, but there is not enough resistance to prevent it completely loosing it and the nail remains weakly magnetised. The supermalloy laminates of a transformer core are not perfectly soft and they will also retain some magnetism, but much less than the nails. When nails and transformer laminates loose their magnetism, we say they are demagnetised

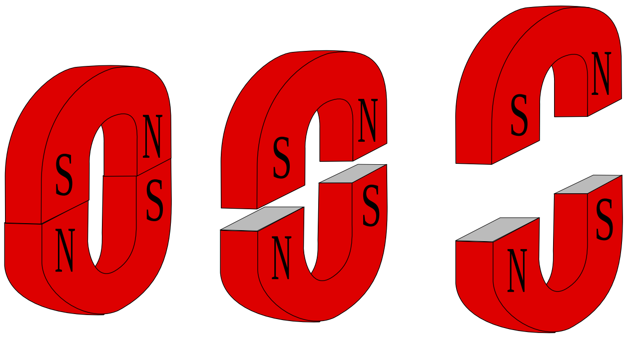
Alnico magnets are not perfectly hard for they will loose some of their magnetism over time and particularly if mistreated. Magnets usually come with a "keeper" made of a soft magnetic material which is used to bridge the gap between the poles. They retain their magnetism longer if the keeper is kept in place. It is however useful for the engineer to design magnets which behave over an operating range as if they were perfect. As long as the magnetic intensity remains within certain limits, there will be no movement of the domain boundaries. However, the flux density within a magnet is reduced if the keeper is removed. If the keeper is replaced, the flux density will be restored. The state produced within the magnet when the keeper is removed is called "reversible demagnetization". It is physically different form the demagnetization of soft magnetic materials because there is no associated movement of the domain boundaries.

A well designed horseshoe magnet comes with a keeper and is designed so that the flux density within the magnet is reduced by half when the keeper is removed. It takes a considerable force to remove the keeper which means that we must do mechanical work. Removing the keeper stores energy. Engineers are taught that this energy is stored in the magnetic field between the poles of the magnet. It is true that the energy content of the magnetic flux between the poles is approximately equal to the work done in removing the keeper, but this is only part of the story for the energy stored in the whole of the magnetic flux is actually reduced by an amount equal to the work done. Both the energy lost from the magnetic field and the energy from the work done in removing the keeper is actually stored in the atoms of the magnet.

To understand what happens we need to have a clear concept of the difference between magnetic intensity H

and magnetic flux density *B*. The aligned electron orbits of a magnet are thought to cancel each other out within the body of the magnet, but to manifest themselves as a net current in the surface of the magnet. This "Amperian" current (named after Ampere) generates the magnetic intensity of the magnet. The magnet is not as solid as we might think because its atoms are composed mostly of empty space in which the electrons orbit the nucleus. The magnetic flux exists in this empty space.

If we take two horseshoe magnets and let them join together as in (a) below, we get a magnetic circuit in which all the flux is contained within the magnets. The Amperian surface currents generate a magnetic intensity *H*. A more useful concept is the magnetomotive force (often called the *mmf*) which is found by integrating *H* around the magnetic circuit. It is akin to the voltage pushing the current round an electric circuit. The flux is akin to the current and there is also a property called reluctance akin to resistance. The reluctance is proportional to the length of the path around the magnetic circuit.



a **b** **c**

If we try to pull them apart by a small distance as in (b) we increase the length of the path by only a small proportion and to all intent and purpose, the flux density remains unaltered. By (c) the path length has increased by about a third and the point will soon be reached when the flux finds a shorter path between the north and south pole of each magnet.

The act of pulling the magnets apart reduces the flux density within the body of each magnet. This is called reversible demagnetization. There is no change in the domain structure or the Amperian current. The flux density has only decreased because of the increased reluctance.

The classical theory was developed before the discover of electrons, let alone the idea that atoms might consist of empty space and orbiting electrons. It is no wonder that classical theory is wrong. Unfortunately, it is still taught and Modern Physics gets more hung up on Einstein's pronouncements that magnetic fields are artefacts of observation to be concerned about the physics taught to children and engineers.

The classical theory gives good answers in well engineered situations and that is good enough to build motors and televisions. But apply it a situation which is engineered differently and it may give funny answers. The fact that there is energy stored in the atoms of a magnet through reversible demagnetization means that experiments can be devised in which some of that energy is recovered and appears to be free energy.

By identifying the energy stored in the atoms during reversible demagnetization, we have brought the theory of magnets in line with the theory of electromagnets and electric motors.

The basic action between an electric current passing through a wire in the presence of a magnetic field consists of a motor action in which $2W$ of electric energy produces W of mechanical energy and stores the other *W* of energy in the magnetic field. We find this to be true in the case electromagnets, but the effect is usually disguised in motors because the energy stored in the magnetic field during one part of the rotation of the motor is then recovered in another, but that is a lesson in advanced electro-mechanical engineering.

Free energy devices

There are innumerable claims that it is possible to build so called "Over Unity Generators" which will extract free energy from the so called "zero point energy" of space. At the point where the inventor claims that this is the way UFOs are powered, as in the case of the Searl Generator, we can stop taking it seriously and have a good laugh. In a conference in 2000, the author listened to many Russian physicists all claiming to have built a devise which consumed 3 kW of power and output 55 kW. Some of these devices were said to be mounted on springs and demonstrated the generation of antigravity!

Needless to say, a significant percentage of the population are willing to invest in such dreams to make it worth while for the fraudsters and the deluded to pedal their wares.

The usual trick is to sit the so called generator between the electricity mains and a set of lightbulbs, then use ammeters and voltmeters to measure the power input and output of the device. With AC electricity, power is not equal to volts x amps. It also depends on the shapes of the wave forms and the phase angle. Use true power meters and the devices are shown to loose energy.

At the more cleaver end of the market, we find the type of apparatus that high school students might use in a science lesson. Since classical theory ignores the potential energy stored in the body of a reversibly demagnetized magnet, there is room to recover some of that energy and claim to have extracted some of the fabled "zero-point energy" of space.