ELECTROMAGNETIC FIELDS

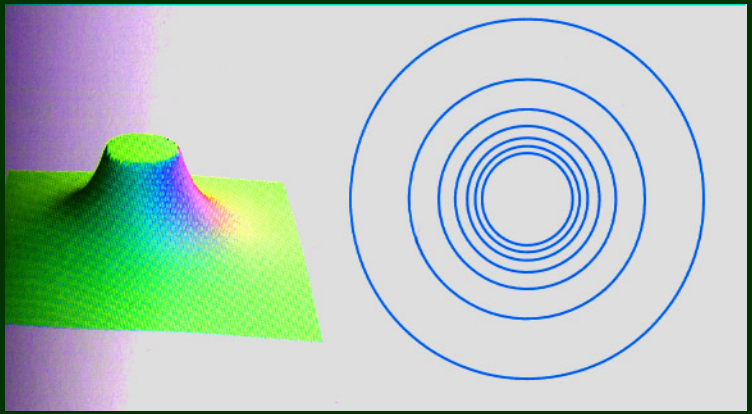
The 19th century led to a triumph of both experimental and theoretical physics, in the unravelling ot eh nature of electrical and magnetic phenomena, and their final synthesis in the idea of an electromagnetic field.

Electrical & magnetic phenomena had been known for millenia, with no real understanding at all of their nature. The triumph of the experimtnal method was to elucidate all their properties by careful experimentation, and to then postulate the existence of invisible electrical and magnetic fields by Faraday, to picture what was going on. All this deployment of the ‘experimental philosophy’ would have made Francis Bacon proud.

The theoretical triumph was to produce a theory which unified all of this (the theory of Maxwell) and which predicted lots of new phenomena (including the existence of electromagnetic waves, which thus firmly revealed the true nature of light – as a wave distortion of the electromagnetic field). All of this deployment of theory to predict new phenomena would have made Huyghens proud.

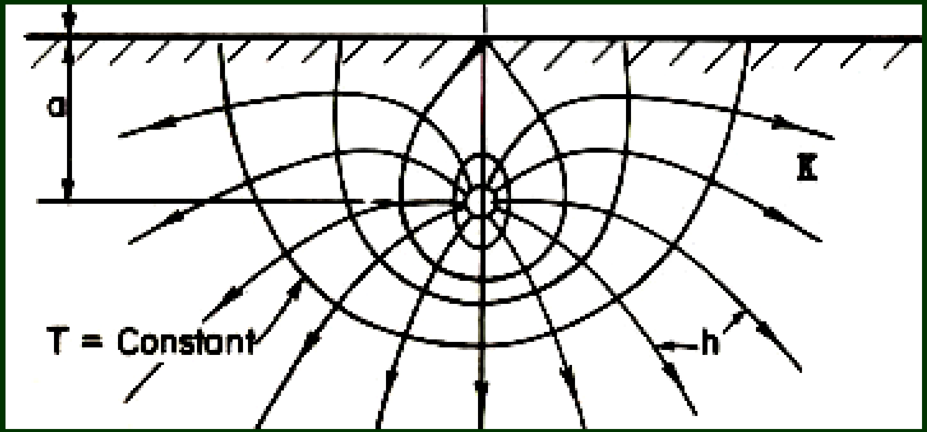
In the following 2 sets of slides this whole development is outlined – beginning with a discussion fo what a ‘field’ is.

POTENTIAL (Scalar) FIELDS



We can also define another kind of field called a SCALAR field, in which one has a scalar (this is a fancy word meaning a NUMBER) at each point (instead of a vector). You will all be familiar with examples of these. At right we show a flat-topped hill- if we make a map of the height (a number) at every point, then we have a scalar field. If we now join up all points having the same value of the scalar, we get a CONTOUR MAP- which is also shown for the flat-topped hill.

Below we see another example- it shows a plate with its boundary running along the top, and a point heat source a distance a below the boundary. Surrounding the heat source we see contours of constant temperature (labelled by T=const). However we also plot some 'streamlines' showing the flow of an associated vector field, which is actually the flow of HEAT (labelled by K). The heat always flows by the shortest path from high to low T, which is why the heat flow streamlines are everywhere perpendicular to the temperature contours.

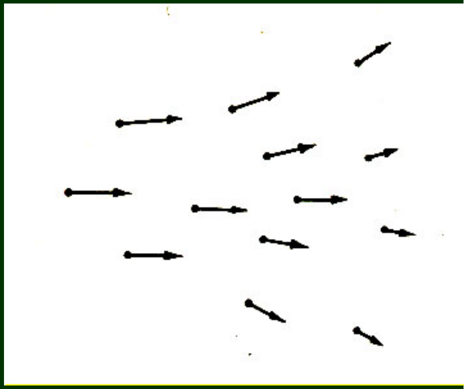


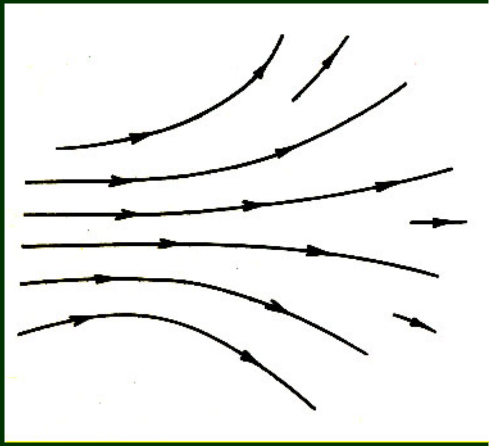
VECTOR FIELDS

This is a simplified intro to the idea of a continuous field. We start with a VECTOR field. Imagine some space (eg., a 2-dimensional space as shown in the pictures). Suppose now that at each point in the space there is "something" that has a magnitude and a direction (ie., it is a vector). Let's note immediately 2 examples:

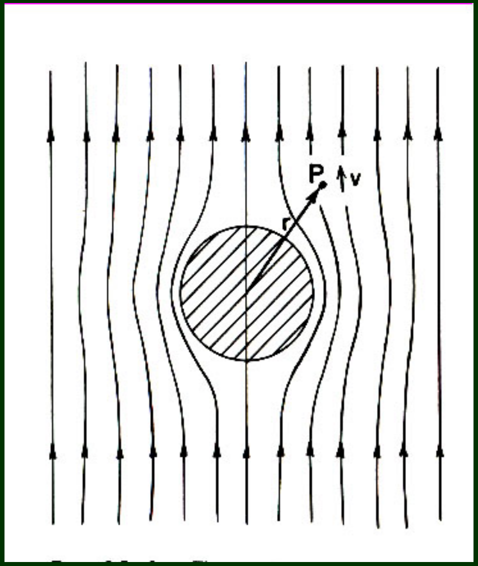
(i) the FORCE field existing in space caused by, eg., some nearby masses- remember that force is a vector.

(ii) the VELOCITY field of a fluid going past a round obstacle (see below).





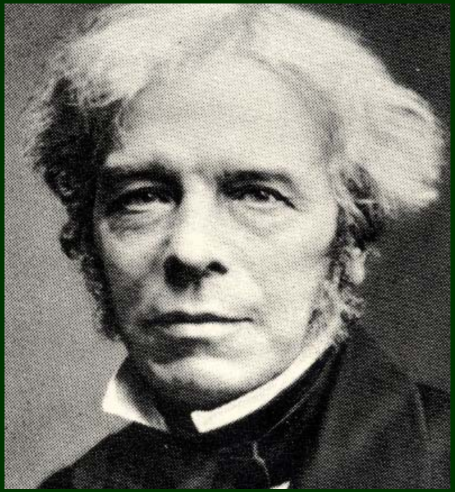
The figure at top right shows what you would get if you measured the vector field at a few select points- the vectors are represented by arrows placed at these points.



The other 2 pictures show "field lines". You can get an idea of what these are by imagining that in the fluid flow at left, one puts a "test particle" down in the fluid at some point. We then trace out the path followed by the particle as it follows the fluid, to get one of the field lines (in fluids, these are often called 'streamlines'). You can imagine doing the same thing with a "test mass" in a gravity field.

The ELECTROMAGNETIC FIELD

In the year 2008, it is still the case that the most important single scientific development for our world has been the understanding of the EM field. Although many played a role in achieving this, the 2 most important advances were made by Faraday, working his whole life in the Royal Institution, and Maxwell, working in Scotland and Cambridge, England.



M. Faraday (1791-1867)

In a long series of experiments Michael Faraday was led to his idea of electric and magnetic field lines- which he viewed as force fields which could move and had their own dynamical properties (such as a "string tension"). His understanding led him to many useful inventions, including the dynamo.

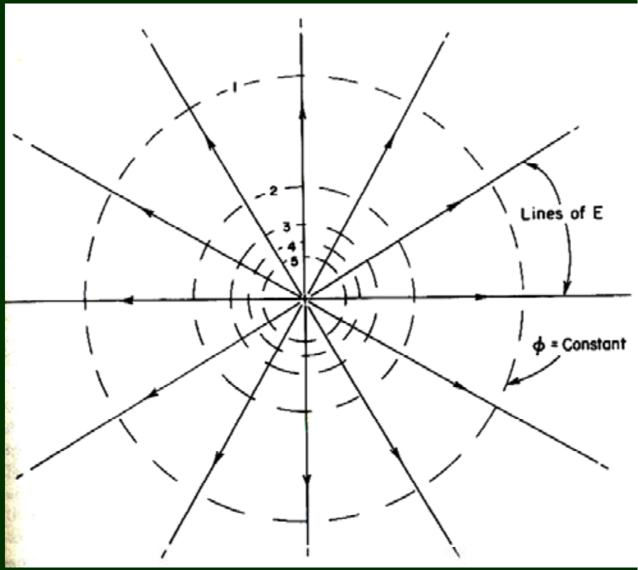
J.C. Maxwell (1831-1879)

Maxwell made fundamental contributions to many parts of what we now call theoretical physics- a subject he did much to create. He gave the first theory of the EM field, an entity which he invented to explain the existing results. This field combined the electric and magnetic fields, and their charge sources, into one.

ELECTROSTATIC FIELDS I

We begin with simple electric field coming from static charges. The field from a single electric charge q_1 has a strength looks just like the gravitational field from a mass- it has a strength which goes like (here k is a constant):

$$E = k \; q_1 / r^2$$



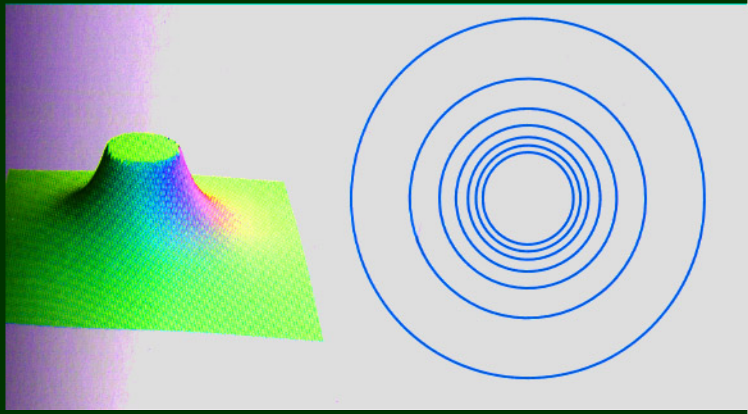
Field lines from +ve charge

and the force on a second charge q_2 is $F = Eq$, so that we can write

$$F = k \; q_1 q_2 / r^2$$

Just as with the gravitational interaction, we can say that this force comes from an electrostatic potential

$$V(r) = - k \; q_1 / r$$

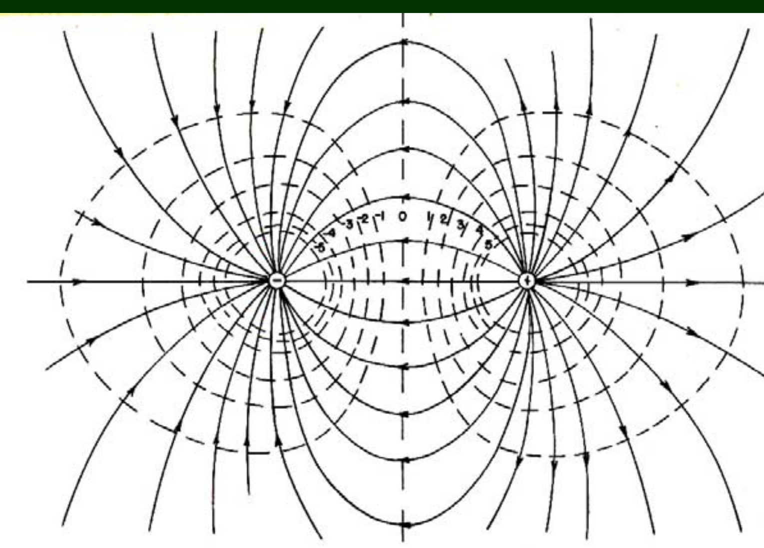

Electrostatic potential from +ve charge

However there is a crucial difference between electrostatic and gravitational forces- the charges q_1, q_2, etc., can be positive or negative (whereas masses can only be positive). Thus electrostatic forces can be attractive or repulsive.

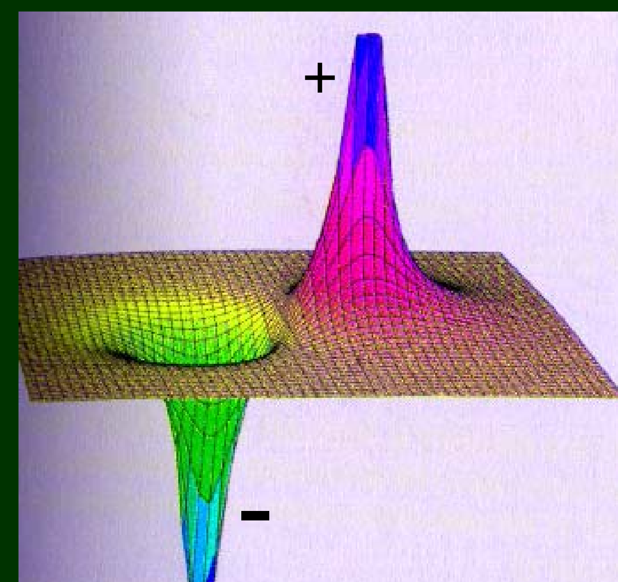
ELECTROSTATIC FIELDS II

A very interesting field configuration is the "dipolar" field, produced by a pair of oppositely charged particles. Of course these 2 charges attract each other- however, what we learn from the pictures below is how the electric field extends away from the dipole, measured by what forces act on some test positive charge. This positive charge is repelled by the positive charge in the dipole (which acts as a potential "hill"), and attracted by the negative charge (which shows a potential well).

The interesting thing is that no matter how far away we get from a dipole, the field from the +ve and –ve charges never exactly cancel (actually the field decreases proportionally to $1/r^3$, instead of the $1/r^2$ dependence that one gets for a single isolated charge.

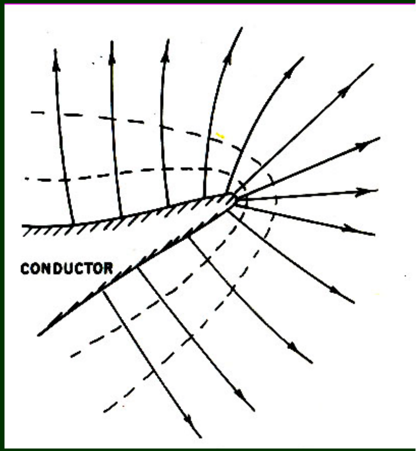


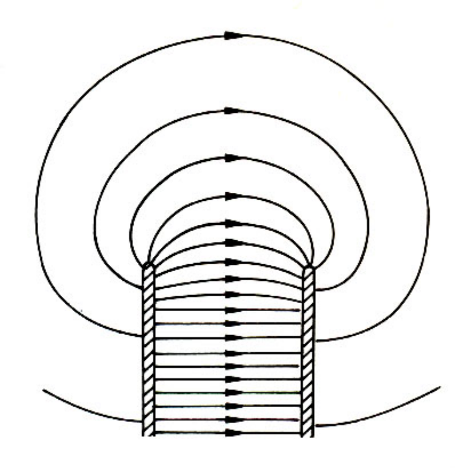
At right is the potential generated by a pair of opposite charges. At left the equipotential contours for this potential are shown as dashed lines, and the electric field lines are shown as continuous lines, flowing from high to low potential.



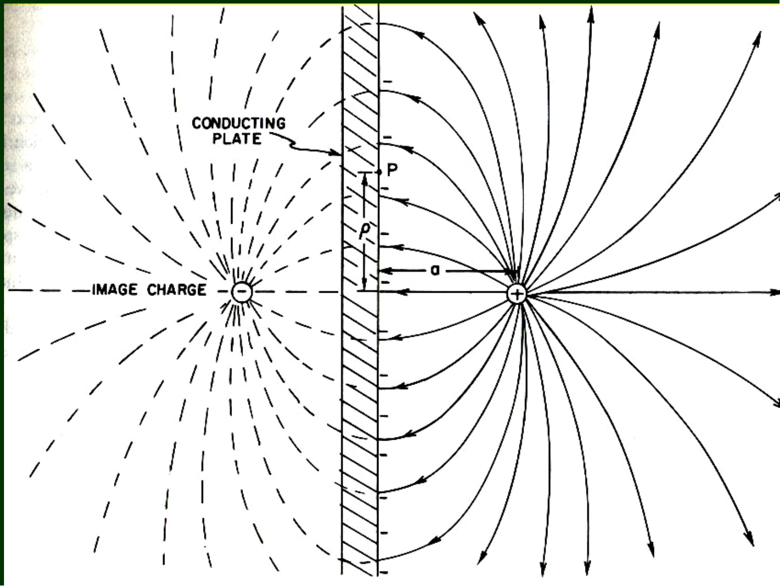
ELECTROSTATIC FIELDS III

In an electric conductor like a metal, electrons will flow until the system is everywhere at the same electrostatic potential (if not, there would still be forces on them causing them to flow!). This all electric field lines from charges on a conductor must come out perpendicular to the surface. A sharp point has a very strong electric field near its surface, coming from the charges on the surface (used, eg., in lightning conductors).



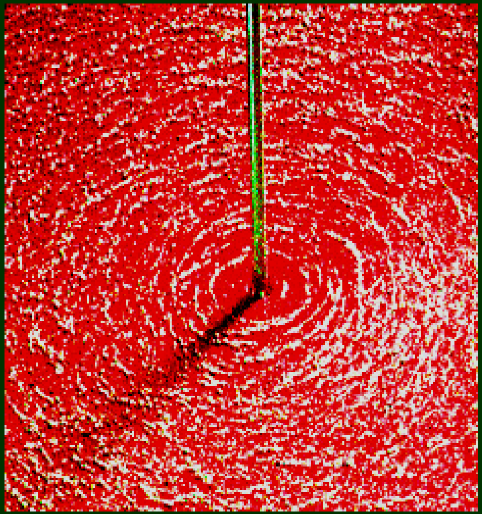


Between 2 long flat plates one gets almost parallel electric field lines, as in a capacitor (at left). Note that at the end of the capacitor field leaks out. Capacitors store + charges on one plate, and – charges on the other; and store the electric field between the 2 of them, with an associated electric field energy.



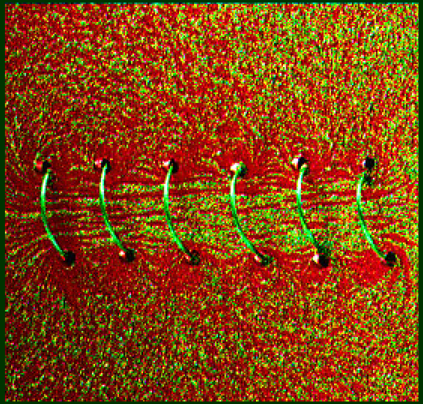
Finally, notice the field configuration when we put a charge near a conducting plate. The field lines again come in perpendicular to the surface, creating one half of what looks like a dipolar field pattern, with a fake "image charge" on the other side of the surface.

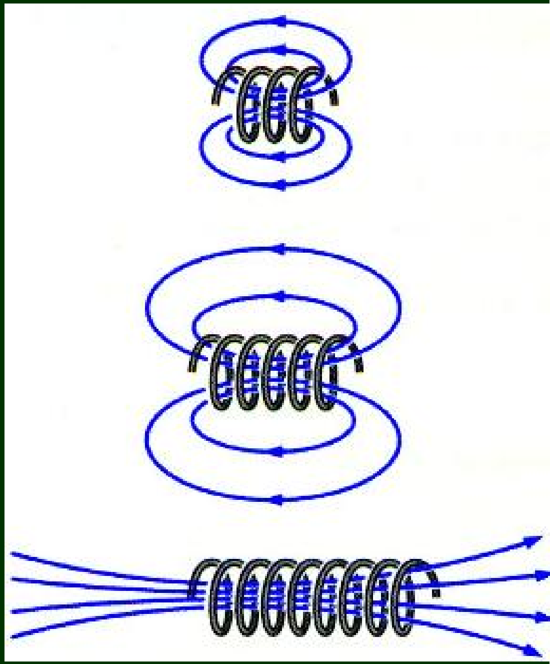
MAGNETIC FIELDS generated by ELECTRIC CURRENTS



One secret of magnetic fields is revealed when we use magnetic probes, like tiny magnetized iron filings, to show the field pattern around current-carrying wires.

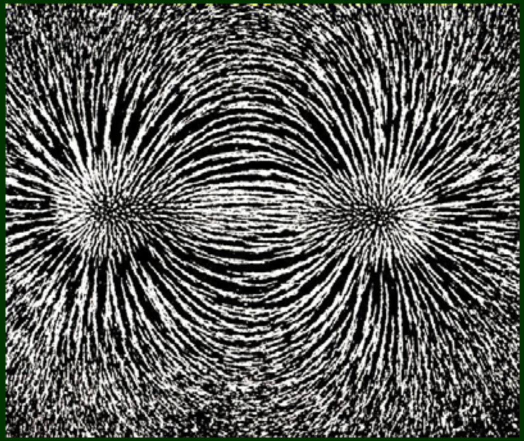
The magnetized filings will lower their energy by aligning their fields to be parallel to the field generated by the current. We see that the current generates a field which "CIRCULATES" around the current, just like fluid circulating around a vortex. A current loop or ring generates a "vortex ring" pattern of field. If we add a lot of rings in parallel (by making a long coil, called a "solenoid"), we get a strong field down the inside of the solenoid, which then spreads out on emerging, eventually curling round to return.

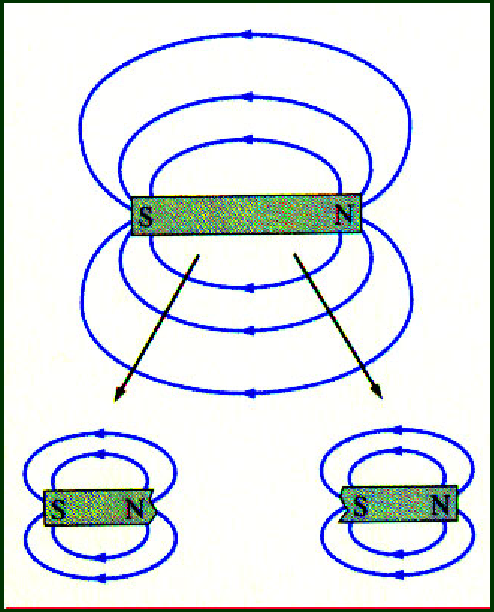




Notice there are no magnetic poles (despite searches they have never been found). Magnetic fields in Nature are generated by current loops.

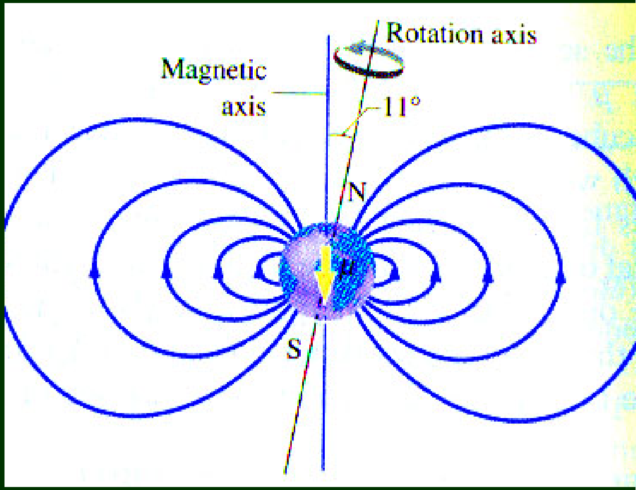
MAGNETOSTATICS





If magnetic fields are caused by electric currents, then how do permanent magnets create fields, and why do they respond to them the way they do?

At right we see the magnetic field pattern due to a long bar magnet. At first glance it looks as though we have magnetic monopoles at the 2 ends of the magnet, but a closer look shows that the field pattern is like that of a solenoid. If we break the magnet in 2 pieces, we just get a lot of little magnets, each acting like a solenoid. Now in reality magnetism comes from the tiny fields from each atom- and each of these behaves like a tiny current loop (something we shall understand when we come to quantum mechanics). If these all line up to produce parallel fields, the result is a magnet. Heating a magnet causes the atomic magnets to lose their alignment, and point in all directions- the fields all then cancel each other and the magnet loses its magnetism.



The earth generates a magnetic field- it comes from Iron and weak electrical currents in the core- both roughly aligned with the rotational axis.