Notes on Electric and Magnetic Properties of Matter.

Electric properties.

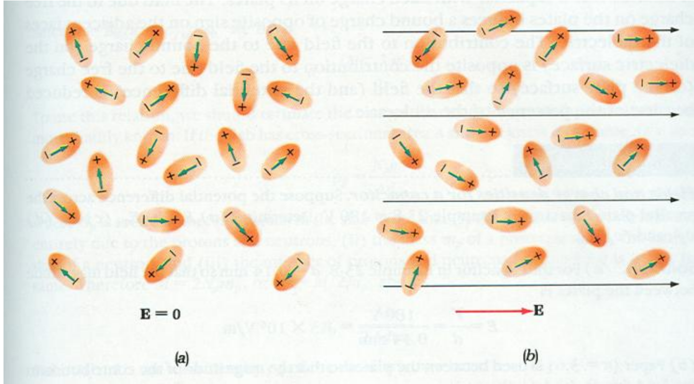
If two charges of equal magnitude and opposite sign are separated by a small distance we call this an electric dipole. Most atoms and molecules are either already electric dipoles or will become electric dipoles in an applied magnetic field. For example although a water molecule is neutral over all, one end (the oxygen end) has slightly more negative charge and the hydrogen ends are slightly positive (H_20 is actually tri-polar but it can be considered approximately dipolar). It is the polar nature of water that gives it many of its special properties (it is a good solvent and it forms special bonds called hydrogen bonds because of the polar charge distribution).

The dipole or dipole moment is give by: $\vec{p} = q\vec{a}$ where q is the magnitude of one end of the dipole and $\vec{a}$ is a vector which gives the magnitude of the separation of the two charges and goes points from the negative to the positive charge (note that the electric field of the dipole is in the opposite direction).

The net force on a dipole in a uniform electric field is zero but there is a torque, $\vec{\tau} = \vec{p} \times \vec{E}$.

The energy stored in a dipole in an electric field is $U = -\vec{p} \cdot \vec{E}$ in joules. The negative sign comes about because we define a dipole to have zero potential energy when it makes a 90^{o} angle with the electric field (remember that, like the *h* in *mgh* for gravitational potential, we can choose where to measure zero from). So the *change* in energy in going from and angle of zero degrees to an angle of 180^{o} is $\Delta U = 2pE$.

In a uniform external electric field dipoles will line up with the positive end downstream and the negative end upstream (the positive end tries to fall in the direction of the electric field and the negative end tries to go the other way). So dipoles in an external electric field have the effect of *weakening* the external electric field because the field of the dipole (going from positive to negative) will be opposite to the external field.



In the picture above with the electric field turned on (b) the net effect is to have a little extra positive charge on the right side of the sample and a little extra negative charge on the left because of the new orientation of the dipoles. The net electric field will be *less* than the applied field because the resulting field of the dipoles is opposite the applied electric field.

A material which has dipoles which react this way or which will become polar in an electric field is called a dielectric material (the prefix *dia* comes from the Greek and means *against*). The amount of weakening of the field is given by an empirical constant called the dielectric constant, κ.

In all of our equations for electric field, the only thing that needs to be changed if the a dielectric material is present is that the dielectric constant multiples the permittivity constant, ε_o. So Coulomb and Gauss' laws become $\vec{E} = \frac{1}{4\pi\kappa\varepsilon_o}\frac{q_1 q_2}{r^2}\hat{r}$ and $\oint \vec{E} \cdot d\vec{A} = \frac{q}{\kappa\varepsilon_o}$. The energy density (Joules per cubic meter) of an electric field is given by $u = \frac{1}{2}\kappa\varepsilon_o E^2$.

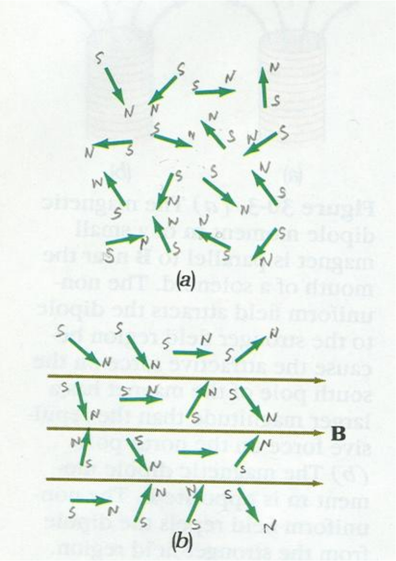
Magnetic properties.

There are no individual magnetic poles like in the case of electric charges so all magnetic fields are dipolar in nature. The electron configuration of an atom determines whether it has a magnetic field or not. As in the case of the electric dipole we can describe this atomic magnetic field as a magnetic moment. For a small wire loop with area *A* and current *I* the magnetic moment is $\vec{\mu} = I\vec{A}$. (A crude but useful picture of an atom is to think of the electrons going around the nucleus as creating a current flow which gives rise to a magnetic moment. This isn't quite right, the magnetic moment of the orbital motion is a quantum mechanical effect which we will talk about later but this is a useful picture to have in your mind.)

The net force on a magnetic moment in a uniform magnetic field is zero but there is a torque, $\vec{\tau} = \vec{\mu} \times \vec{B}$.

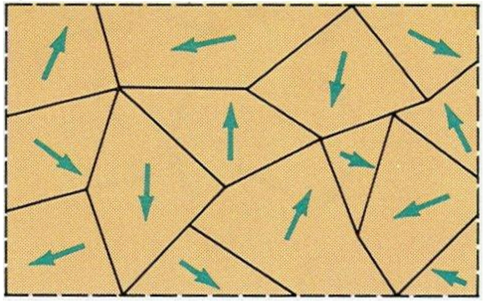
The energy stored in a magnetic moment in an electric field is $U = -\vec{\mu} \cdot \vec{B}$ in joules. The negative sign comes about because (like the case for the electric dipole) we define a magnetic moment to have zero potential energy when it makes a 90^o angle with the magnetic field. So the *change* in energy in going from and angle of zero degrees to an angle of 180^o is $\Delta U = 2\mu B$.

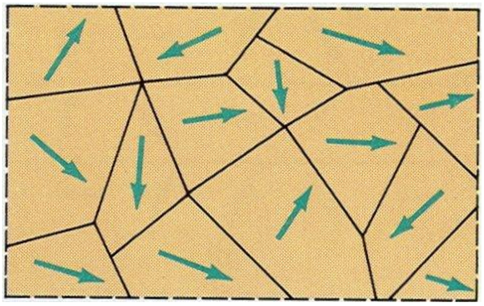
Unlike electric dipoles which weakens an externally applied electric field, the alignment of magnetic moments with an external magnetic field *strengthens* the external field. This effect is called paramagnetism and it occurs for about half the elements on the periodic table (the prefix *para* comes from the Greek and means *for*).



In the above figure, when the external magnetic field is turned on (b) the moments line up with the field to some degree but this time there will be *more* field on the left and right (more magnetic field lines will exit the right side of the sample and enter the left because of the arrangement of the moments so the right side is a *stronger* magnetic north pole and the left a stronger magnetic south pole).

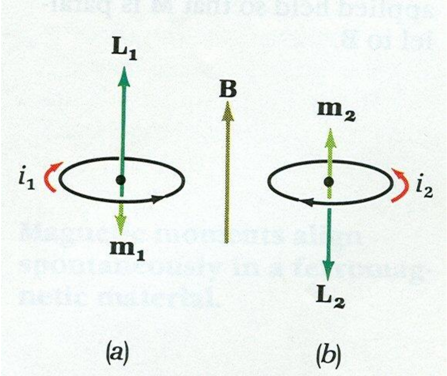
For three elements, Fe, Ni and Co, the electron configuration causes neighboring atoms to interact in such a way that the magnetic moments combine and remain lined up in domains or regions of atoms, even with no external magnetic field. This effect is called ferromagnetism. If the domains line up and stay that way we have a permanent magnet. If the domains are randomly oriented the material is not a magnet but it will greatly strength an applied external magnetic field because the domains will temporarily line up with the external field. The picture on the left shows domains which are not lined up. The picture on the right shows a material with some of the domains lined up so that the material has a net magnetic effect.





The electron configuration of an atom can react in a third way when exposed to an external magnetic field. All atoms react this way to some extent but often the effect is masked by para- or ferro- magnetic effects. A crude but useful way to understand diamagnetism is to imagine a pair of electrons circulating in opposite directions in the same plane around the nucleus. Without any external magnetic field we would expect the two magnetic moments of each electron's orbit to cancel since they are going in opposite directions (one creates a magnetic moment upward, the other downward for example).

But if an external magnetic field is applied we would expect a Faraday law like effect to cause one of the electrons to speed up slightly and the other to slow down. The result is that the electron orbits give the atom a net magnetic moment which will be *opposite* to the external magnetic field. This *weakening* of the applied magnetic field is called diamagnetism. The effect can be strong enough that the material is actually repelled by the external magnetic field (scientists have been able to use the effect to levitate living organisms and other objects which are not ferro- or para- magnetic. The two figures below represent two electrons in the *same* atom. L is the angular momentum and m is the magnetic moment. With the applied magnetic field, B the magnetic moment of the electron shown on the left is stronger ($m_1 > m_2$) so there is a net magnetic moment opposite to the applied field.



Similar to the case of materials which react to electric fields the amount of change of the externally applied magnetic field when applied to a magnetic material can be expressed by an empirical constant called the diamagnetic or paramagnetic constant, κ_m .

In all of our equations for magnetic fields, the only thing that needs to be changed if a magnetic material is present is that the dielectric constant multiples the permeability constant, μ_o. So the Biot-Savart law and Ampere's laws become $d\vec{B} = \frac{1}{4\pi\kappa_m\mu_o}\frac{Id\vec{l}\times\hat{r}}{r^2}$ and $\oint \vec{B}\cdot d\vec{l} = \kappa_m\mu_o I$. The energy density (Joules per cubic meter) of a magnetic field is given by $u = \frac{1}{2}\frac{B^2}{\kappa_m\mu_o}$.

The orbital configuration of the electrons around an atom give rise to an orbital magnetic moment. The protons, neutrons and electrons themselves also have individual magnetic moments (usually called spin). The detection of spin and techniques based on spin resonance (electron spin resonance and nuclear magnetic resonance a.k.a. magnetic spin resonance) are magnetic phenomena which take advantage of the fact that these individual atomic components have a magnetic moment. All of these magnetic moments interact with each other which gives rise to coupling (for example spin- orbital coupling). The effects can be quite complex but the underlying principle is simple: individual atomic components (even quarks) have a magnetic moment and the orbital configuration of an electron has a magnetic moment.