Electromagnetism

Magnetism

In spite of living inside the magnetic field of the Earth and knowing about some magnetic effects for thousands of years (the compass was invented 200 BC, and the tale of the Magnetic Mountain in *One Thousand and One Nights* is from 800 AD), it is only in modern times that we started to understand magnetism. Perhaps what caused the delay is the strange fact that the magnetic force is orthogonal to the field, not parallel to it, and its dependence on velocity.

Lorentz magnetic force

$$\vec{F} = q\vec{v} \times \vec{B}$$

F is the magnetic force, *q* is the charge, *v* the velocity and *B* the magnetic field. The cross symbol (×) signifies vector multiplication that generates another vector perpendicular to both, *v* and *B*, and proportional to the sine of the angle between them. The fact that the magnetic force comes out of a vector multiplication certainly confused our great grandparents or perhaps they had other things to worry about.

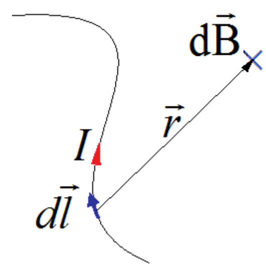
This equation is part of a longer one that includes the electrostatic force due to electric fields. The full equation is called the Lorentz force equation.

$$\vec{F} = q\vec{v} \times \vec{B} + q\vec{E}$$

Because the magnetic force equation has five magnitudes (force, charge, velocity, magnetic field and angle), it is possible to calculate any of those quantities if you know the other four, so this could be the basis for a magnetic sensor. How would you build one? I challenge you to design a sensor based on this equation.

Going back to our scientific ancestors, they also had the challenge of understanding how to generate a magnetic field *B*. In the 19^{th} century it was thought that electricity and magnetism were independent phenomena, but Oersted demonstrated their interrelation. Now we know that electric currents generate magnetic fields according to the law of Biot and Savart.

Biot and Savart Law



$$d\vec{B} = \frac{\mu_0 I d\vec{l} \times \vec{r}}{4\pi r^3}$$

It is traditional that when you study magnetism you learn how to calculate magnetic fields generated by simple current carrying wire structures such as circular loops, coils, long wires, etc. These exercises have value in helping get insight in how fields are generated, however if you deviate a bit from those simple cases the analytical solutions are usually very complicated. In practice you can use the law of Biot and Savart to calculate the field generated by short sections of wire and then add the vectors numerically.

Besides generating magnetic fields with currents through wires there are permanent magnets. Think of all those that are attached to your refrigerator door. Where are the currents there? As hard as it is to believe, those are sub-atomic “currents” due to the spin of the electron!

The electron has a strange characteristic: it is always rotating on its own axis. This rotation cannot be stopped without destroying the electron. Associated with this rotation there is an angular momentum called spin (recall your chemistry) and also a magnetic moment as if it were a circular loop carrying current. The electron behaves as a tiny magnet. In many materials like copper or gold, these magnets are oriented in a disordered way, so in average their magnetic moments add to zero, but in certain materials (like iron) they conspire to point in the same direction to give the same effect as a macroscopic current.