home

Physics 2415 Lecture 14: Magnetism I

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Early Observations and First Use

No doubt people were aware of magnetic and electrical phenomena much earlier, but the first recorded magnetic observations are from about 500 BC, the ancient Greeks. Rocks were observed to attract each other, and stick to iron nails in boots, in a place called Magnesia.

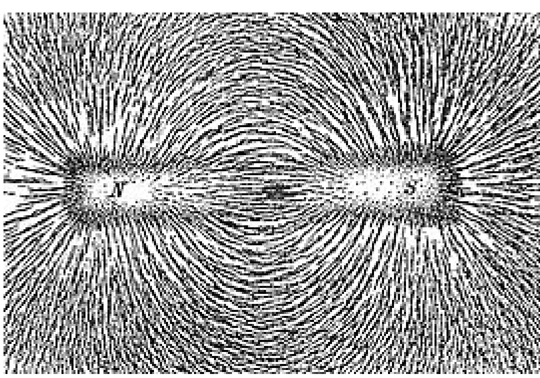
The first important use of magnetism was that of the compass in navigation. This was in approximately !000 AD in Northern Europe, and about the same time in China. (Apparently the Chinese had magnetic pointing devices earlier, but these were not used for navigation, only for finding most harmonious direction arrangements for furniture, etc., *feng shui*). The approximately simultaneous arrival of the navigational compass in Northern Europe and China suggests a common source, perhaps the Mongols, this is much discussed on the web, but the lack of documentation from this period renders it inconclusive, at least as far as I can see.

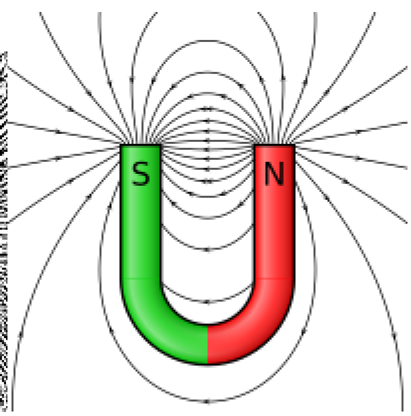
The first attempt to analyze magnetism from a recognizably modern point of view was the publication of *De Magnete* in 1600 by William Gilbert of St John's College, Cambridge (my college). He constructed a miniature earth (terrella) of lodestone and moved a small compass around its surface to demonstrate that the Earth itself was in fact a magnet. His work impressed Galileo, in fact their approaches were very similar, both had little patience for "authorities" who didn't do experiments.

For a fuller account of the development of these ideas, check out my notes here.

Magnets 101

Everyone is familiar with bar magnets, horseshoe magnets, and revealing the magnetic field by sprinkling iron filings, which line up with the field. There are always two "poles", labeled N and S from compass notation (N for "north seeking"). Like poles repel, unlikes attract.



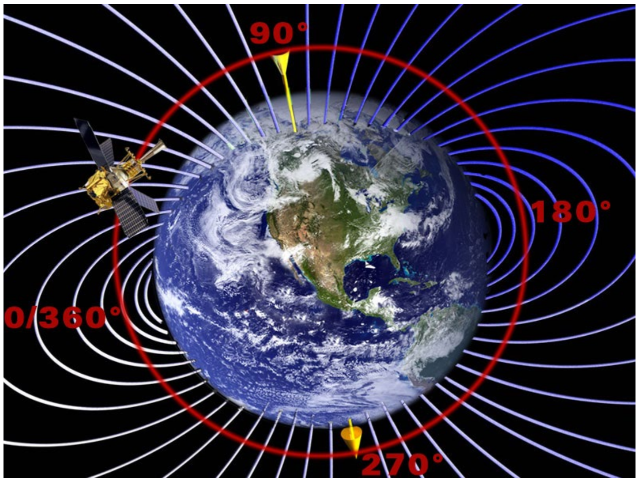


The iron filings make clear that the field pattern, especially some distance away, resembles the electric field from equal positive and negative charges close to each other, a dipole. But it's really quite different! You can have an isolated positive charge, you can't have an isolated magnetic north pole. If you break the bar in two, each piece will have its own N and S pole area.

The horseshoe magnet is a convenient configuration to concentrate the strong field into a small volume.

Powerful compact magnets are essential for building electric cars, and it turns out iron is not magnetic enough—the solution is to alloy with rare earths, in particular neodymium and dysprosium. Currently (2024) these are almost all mined in China, but can be found elsewhere, for example Ukraine and Greenland.

The Earth's Magnetic Field



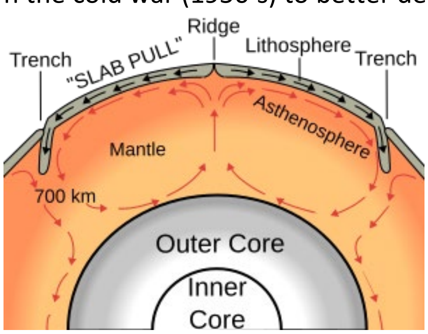
Although the Earth's core is mainly iron, it is too hot to be magnetized (thermal vibrations knock the magnetic atoms out of line with each other).

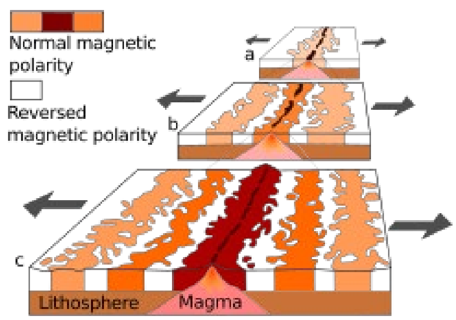
The Earth's magnetic field is actually generated by electric currents in the outer core, driven by a combination of convection fluid currents and Corioli's forces. It is not a simple process.

The general shape is as perceived by Gilbert, a dipole (with the S end under the North pole, approximately). It is not in line with the Earth's axis of rotation, and in fact it has been proved that the fluid dynamics generating the dipole field would not work if it *was* in line.

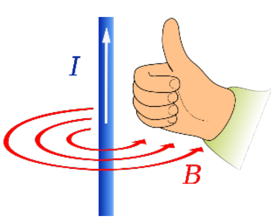
Seabed Stripes

n the cold war (1950's) to better detect submarines magnetically, a detailed map of seabed magnetization in the Atlantic was made. It revealed a pattern of stripes of *reversed* magnetization, symmetric about the midatlantic ridge. This cast light on continental drift: hot materials well up at the ridge, get magnetized as they cool in the Earth's field, spread out both ways. And, it turns out, the Earth's magnetic field sometimes *reverses*, about every 300,000 years. Of course, any theory that explains the Earth's magnetization will have to include this.





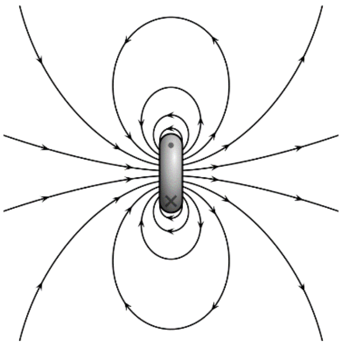
Oersted's Great Discovery



In 1820, the Danish physicist Oersted was the first to show electricity and magnetism were connected, by detecting the magnetic field of an electric current: remarkably, the field *circled around*, direction given by the right-hand rule (see figure). Here's a demo.

Notice how very different these field lines are from any possible static electric field. If you have a north pole, you can take it around a circle and end up at higher energy—evidently, unlike the static electric field, this field doesn't come from a simple potential.

Currents in Loops and Solenoids

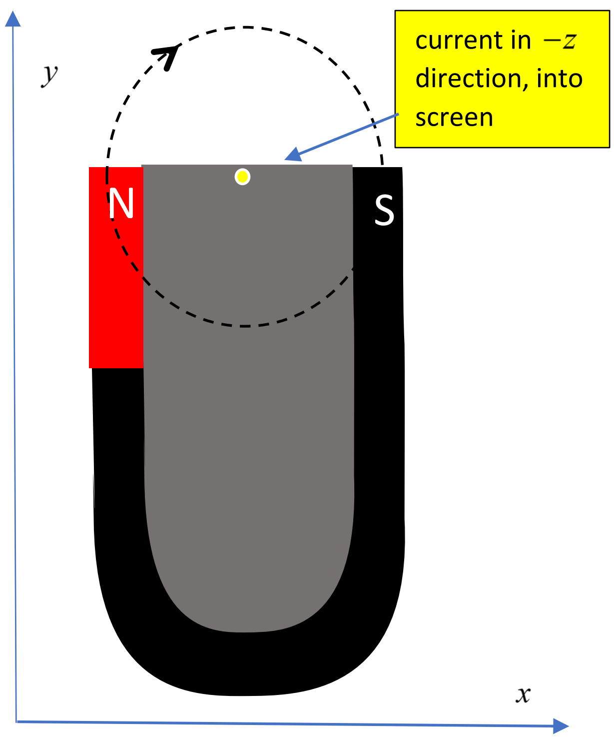


Bending the wire into a circle, we can figure out the general shape of the field. Note that a *solenoid* (a series of connected loops) has a field resembling a bar magnet—but now we can see inside, and there are no poles. The magnetic field lines don't stop anywhere. No-one has ever detected a magnetic monopole, despite many expensive attempts, and at least one false alarm.

Loop by Geek3 - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=11621875)

Solenoid by Maciej J. Mrowinski - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=125786739

Force on a Horseshoe Magnet from Current in Wire and *Vice Versa*



In the diagram, the circle is a line of magnetic force from current going *downwards* in a wire perpendicular to the picture, passing through the yellow dot half way between the poles. Note the axes: this is a 3D problem.

The crucial point is that the magnetic force on the S pole is equal to and *parallel with* that on the N pole—the forces *add*!

So the horseshoe feels an upwards force, meaning in the y-direction in the diagram.

From Newton's Third Law, then, the wire must experience a downward ($-y$) force from the horseshoe's magnetic field. That field, of course, is going from N to S, so is in the positive x-direction at the wire. Remembering the current is downwards ($-z$) into the diagram, the force is evidently in the direction *perpendicular both to the wire and the magnetic field*.

Definition of Magnetic Field

The magnetic field strength $\vec{B}$ is defined by this force: for a uniform field, straight wire increment $\overrightarrow{d\ell}$,

$$\vec{F} = I\overrightarrow{d\ell} \times \vec{B}.$$

This result is well-established experimentally for any angle between the wire and the field, and in particular for a current running parallel to the field there is zero force.

This equation fixes the unit of magnetic field: for $\vec{F}$ in Newtons, I in amps, $\vec{B}$ is in *Teslas*.

Force on Any Current in a Constant Field

It is found experimentally that the total magnetic force on any wire carrying current I in a constant magnetic field $\vec{B}$ is the sum of terms $d\vec{F} = I\overrightarrow{d\ell} \times \vec{B}$.

For a constant magnetic field, for any shape wire going from $\vec{r}_1$ to $\vec{r}_2$,

$$\vec{F} = I\left(\int_{\vec{r}_1}^{\vec{r}_2} \overrightarrow{d\ell}\right) \times \vec{B} = I\left(\vec{r}_2 - \vec{r}_1\right) \times \vec{B},$$

The little $\overrightarrow{d\ell}$ vectors are head to tail, they all add to give the straight line from $\vec{r}_1$ to $\vec{r}_2$.

This means that for a closed loop of current in a constant field there is no net force—but there *is* in general a couple acting, as we'll soon discuss.