Introduction to magnetism

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March 11, 2013

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1 Historical overview

The phenomenon of magnetism has been known to mankind for many thousands of years and consists in the ability of some materials, called *magnets*, to attract small pieces of iron, cobalt, nickel and their alloys. Loadstone, which is a naturally magnetized piece of the mineral *magnetite*, was the first permanent magnetic material to be identified and studied. The Greek word *magnes*, which is the root of the English word *magnet*, is derived from Magnesia, the name of an ancient city in Asia Minor, which, presumably, was once a copious source of loadstones. Since magnetite is already magnetized when found in nature, it is called *natural magnet*. Magnets that are made by man are called *artificial magnets*.

The *magnetic compass*, which is obtained by magnetizing an iron needle by contact with another magnet, was invented some time during the first ten centuries AD. Credit is variously given to the Chinese, the Arabs, and the Italians. What is certain is that by the 12th century magnetic compasses were in regular use by mariners to aid navigation at sea. In the 13th century, Peter Perigrinus of France discovered that the magnetic effect of a spherical loadstone is strongest at two oppositely directed points on the surface of the sphere, which he termed the *poles of the magnet*. He found that there are two types of poles, and that *like poles repel one another whereas unlike poles attract*. In 1600, the English physician William Gilbert concluded, quite correctly, that the reason magnets like to align themselves in a North-South direction is that the Earth itself is a magnet. Furthermore, the Earth's magnetic poles are aligned, more or less, along its axis of rotation. This insight immediately gave rise to a fairly obvious nomenclature for the two different poles of a magnet: a magnetic north pole (N) points towards the geographic north pole of the Earth, whereas a magnetic south pole (S) points towards the geographic south pole of the Earth. Therefore, the magnetic field of the Earth can be seen as generated by an ideal *magnetic bar* having the magnetic south pole close to the north geographic pole and vice-versa. When a compass needle points towards the geographic north, the north pole of the needle is attracted by the magnetic south pole of the Earth. In other words, *the north pole of a magnet is so defined because it is attracted towards the Earth's north pole*.

Another British scientist, John Michell, discovered in 1750 that the attractive and repulsive forces between the poles of magnets vary inversely as the square of the distance of separation. Thus, the inverse square law for forces between magnets was actually discovered prior to that for forces between electric charges.

2 First experiments

2.1 Oersted's experiment

On 21 April 1820, the Danish physicist Hans Christian Oersted was giving a lecture demonstration of various electrical and magnetic effects. Suddenly, much to his amazement, he noticed that the needle of a compass he was holding was deflected when he moved it close to a current carrying wire, as reported in figure 1. This was a very surprising observation, since, until that moment, electricity and magnetism had been thought of as two quite unrelated phenomena.

Figure 1: Oersted's experiment

His initial interpretation was that magnetic effects radiate from all sides of a wire carrying an electric current, as do light and heat. Three months later he began more intensive investigations and soon thereafter published his findings, showing that an electric current produces a circular magnetic field as it flows through a wire. This discovery was not due to mere chance, since Oersted had been looking for a relation between electricity and magnetism for several years.

2.2 Faraday's experiment

Faraday discovered that a straight wire carrying an electric current experiences a force when it is immersed in a magnetic field.

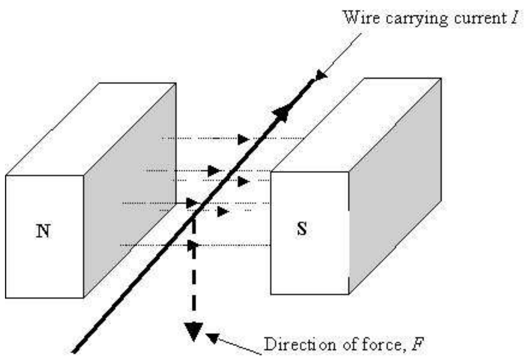

Figure 2: Faraday's experiment

In particular, the force is perpendicular to both the wire and the magnetic field, as shown in figure 2.

2.3 Ampère's experiment

During September and October 1820, Ampère, influenced by Oersted's discovery, performed a series of experiments designed to elucidate the exact nature of the relationship between electric current-flow and magnetism, as well as the relationships governing the behavior of electric currents in various types of conductors. Among others, Ampère showed that two parallel wires carrying electric currents magnetically attract each other if the currents are in the same direction and repel if the currents are in opposite directions (see figure 3).

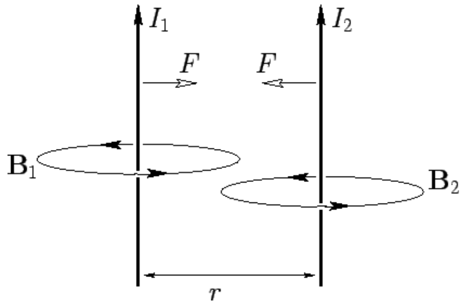

Figure 3: Ampère's experiment

This experiments led Ampère to formulate his famous law of electromagnetism, called after him Ampère's law, that describes mathematically the magnetic force between two electrical currents. Consider two parallel wires of length ℓ separated by a perpendicular distance r and carrying electric currents i_1 and i_2, respectively. The magnetic force between the wires is

$$F = \mu \frac{i_1 i_2 \ell}{2\pi r}, \tag{2.1}$$

where the constant of proportionality μ is called the *magnetic permeability* and depends on the material between the two wires. If they are in the free space (vacuum), its value is

$$\mu_0 = 4\pi \times 10^{-7}\,\mathrm{N\,A^{-2}}.$$

Incidentally, Eq. (2.1) is the basis of the official SI definition of the ampere, which is: *One ampere is the magnitude of the current which, when flowing in each of two long parallel wires one meter apart, results in a force between the wires of exactly* 2×10^{-7}*N per meter of length.*

3 Visualization of magnetic field lines

A field line is a line which is tangential, in each point, to the magnetic field.

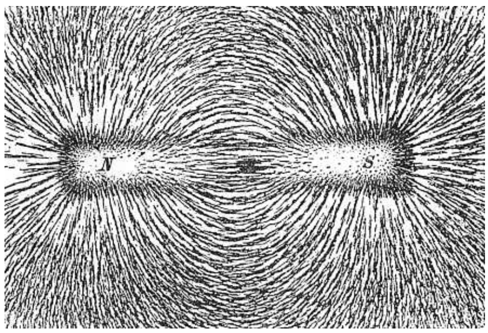

Figure 4: The direction of magnetic field lines is visualized by the alignment of iron filings sprinkled on paper placed above a bar magnet

Visualizing the magnetic field of an object is simple, in principle. First, measure the strength and direction of the magnetic field at a large number of locations (or at every point in space). Then, mark each location with an arrow (called a vector) pointing in the direction of the local magnetic field with its magnitude proportional to the strength of the magnetic field. An alternative method to map the magnetic field is to 'connect' the arrows to form magnetic field lines. The direction of the magnetic field at any point is parallel to the direction of nearby field lines, and the local density of field lines can be made proportional to its strength.

Various phenomena have the effect of "displaying" magnetic field lines as though the field lines are physical phenomena. For example, iron filings placed in a magnetic field line up to form lines that correspond to 'field lines', as shown in figure 4.

By convention, the field lines enter a magnet from the south pole and exit from the magnet at the north pole.

4 Magnetic fields generated by electric currents

4.1 Straight wire

A wire that carries an electric current generates a magnetic whose lines are concentric circles perpendicular to the wire with their centers on the wire itself. The direction of the magnetic field follows the right-hand rule: if the thumb points in the direction of the electric current, the other fingers wrap around the wire in the direction of the magnetic field.

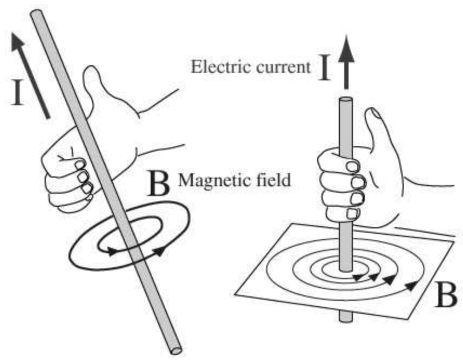

Figure 5: Magnetic field generated by a current in a straight wire

The intensity of the magnetic field generated by a current i at a distance r from the straight wire is give by the Biot-Savart law

$$B = \frac{\mu i}{2\pi r}.$$

4.2 Single loop

Examining the direction of the magnetic field produced by a current-carrying segment of wire shows that all parts of the loop contribute to the magnetic field in the same direction inside the loop.

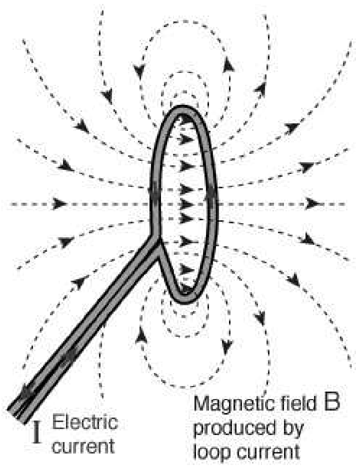

Figure 6: Magnetic field generated by a current in a closed loop

Electric current in a circular loop generates a magnetic field which is more concentrated in the center of the loop than outside the loop. The direction of the magnetic field in the center of a circular curl of radius R along its axis is given by the right-hand rule, whereas the intensity is

$$B = \frac{\mu i}{2R}.$$

4.3 Solenoid

A solenoid is a long, thin loop of wire which produces a uniform magnetic field in a volume of space when an electric current is passed through it. By wrapping the same wire many times around a cylinder, the magnetic field due to the loops can become quite strong and is proportional to the number of turns N.

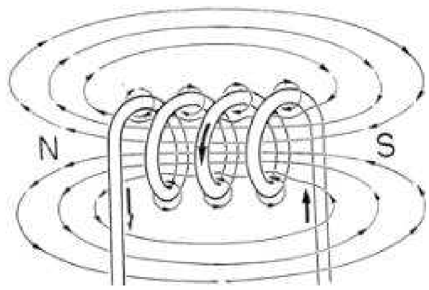

Figure 7: Magnetic field generated by a solenoid

The direction of the magnetic field inside a solenoid follows the right-hand rule (if the four fingers are wrapped around the solenoid following the direction of the current, the magnetic field on the solenoid's axis points in the same direction as the thumb. The intensity of the magnetic on the solenoid's axis is given by the expression

$$B = \mu \frac{N}{L} i,$$

where N/L in the number of loops per unit length and i is the intensity of the electric current,

Solenoids are important because they can generate *controlled magnetic fields*. Electromagnets are solenoids in which the magnetic field is greatly strengthened by the addition of an iron core, which is a ferromagnetic material and enhances the magnetic field by generating a further magnetic field.

5 Questions

1. What is magnetite?
2. What are the metals attracted by magnets?
3. What is the difference between *natural* and *artificial* magnets?
4. How is a magnetic compass made?
5. What is the relationship between geographic and magnetic poles?
6. Describe Oersted's experiment.
7. Describe Ampère's experiment.
8. What is μ? What is μ_0 and what is its value?
9. What is the force between two parallel wires carrying electric currents? Does it depend on the direction of the currents? If so, how?
10. What is a magnetic field line? How can it be visualized?
11. Describe the magnetic field generated by a straight wire carrying an electric current (direction and intensity of the magnetic field).
12. Describe the magnetic field generated by a single circular wire carrying an electric current (direction and intensity of the magnetic field).
13. Describe the magnetic field generated by solenoid carrying an electric current (direction and intensity of the magnetic field).
14. Why are solenoids important?
15. What is an electromagnet?