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Magnetism and electromagnetism

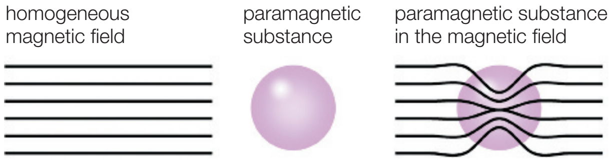

Figure 1.1 Paramagnetic properties.

Figure 1.2 Diamagnetic properties.

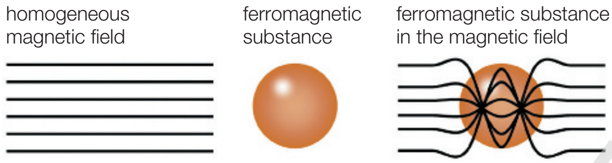

Figure 1.3 Ferromagnetic properties.

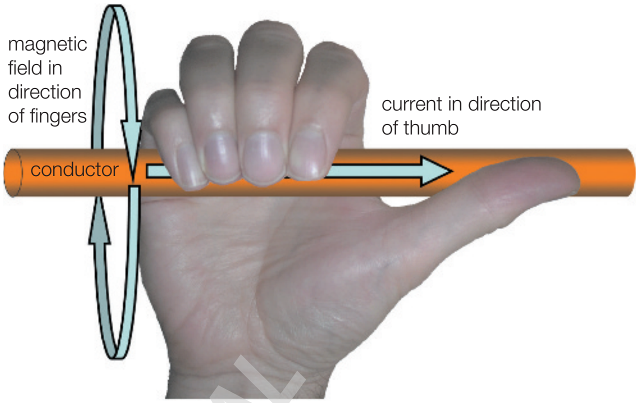

Figure 1.4 The right-hand thumb rule.

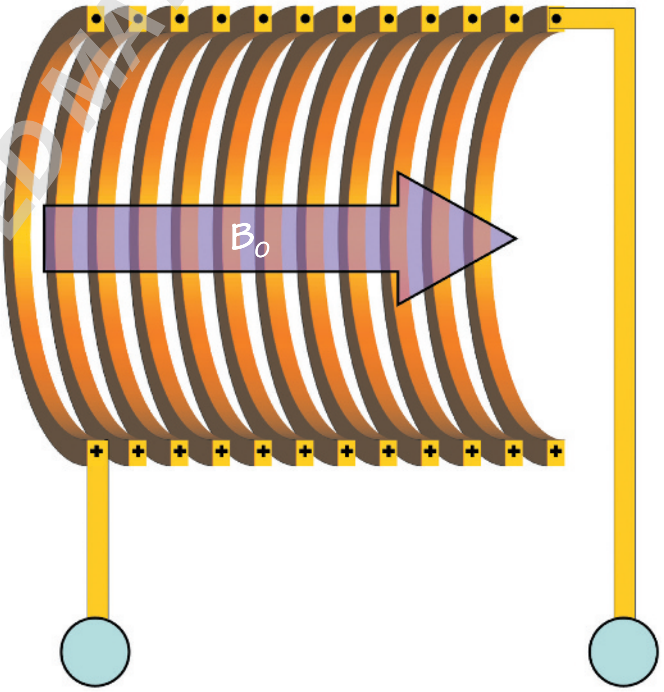

Figure 1.5 A simple electromagnet.

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Magnetic susceptibility

The **magnetic susceptibility** of a substance is the ability of external magnetic fields to affect the nuclei of a particular atom, and is related to the electron configurations of that atom. The nucleus of an atom, which is surrounded by paired electrons, is more protected from, and unaffected by, the external magnetic field than the nucleus of an atom with unpaired electrons. There are three types of magnetic susceptibility: **paramagnetism**, **diamagnetism** and **ferromagnetism**.

Paramagnetism

Paramagnetic substances contain unpaired electrons within the atom that induce a small magnetic field about themselves known as the **magnetic moment**. With no external magnetic field, these magnetic moments occur in a random pattern and cancel each other out. In the presence of an external magnetic field, paramagnetic substances align with the direction of the field and so the magnetic moments add together. Paramagnetic substances affect external magnetic fields in a positive way, resulting in a local increase in the magnetic field (Figure 1.1). An example of a paramagnetic substance is oxygen.

Super-paramagnetism

Super-paramagnetic substances have a positive susceptibility that is greater than that exhibited by paramagnetic substances, but less than that of ferromagnetic materials. Examples of a super-paramagnetic substance are iron oxide contrast agents.

Diamagnetism

With no external magnetic field present, diamagnetic substances show no net magnetic moment, as the electron currents caused by their motions add to zero. When an external magnetic field is applied, diamagnetic substances show a small magnetic moment that opposes the applied field. Substances of this type are therefore slightly repelled by the magnetic field and have negative magnetic susceptibilities (Figure 1.2). Examples of diamagnetic substances include water and inert gasses.

Ferromagnetism

When a ferromagnetic substance comes into contact with a magnetic field, the results are strong attraction and alignment. They retain their magnetization even when the external magnetic field has been removed. Ferromagnetic substances remain magnetic, are permanently magnetized and subsequently become permanent magnets. An example of a ferromagnetic substance is iron.

Magnets are **bipolar** as they have two poles, north and south. The magnetic field exerted by them produces magnetic field lines or lines of force running from the magnetic south to the north poles of the magnet (Figure 1.3). They are called **magnetic lines of flux.** The number of lines per unit area is called the **magnetic flux density**. The strength of the magnetic field, expressed by the notation **(B)** – or, in the case of more than one field, the primary field **(B_0)** and the secondary field **(B_1)** – is measured in one of three units: **gauss (G)**, **kilogauss (kG)** and **tesla (T)**. If two magnets are brought close together, there are forces of attraction and repulsion between them depending on the orientation of their poles relative to each other. Like poles repel and opposite poles attract.

Electromagnetism

A magnetic field is generated by a moving charge (electrical current). The direction of the magnetic field can either be clockwise or counter-clockwise with respect to the direction of flow of the current. **Ampere's law** or **Fleming's right-hand rule** determines the magnitude and direction of the magnetic field due to a current; if you point your right thumb along the direction of the current, then the magnetic field points along the direction of the curled fingers (Figure 1.4).

Just as moving electrical charge generates magnetic fields, changing magnetic fields generate electric currents. When a magnet is moved in and out of a closed circuit, an oscillating current is produced, which ceases the moment the magnet stops moving. Such a current is called an **induced electric current** (Figure 1.5).

Faraday's law of induction explains the phenomenon of an induced current. The change of magnetic flux through a closed circuit induces an **electromotive force (emf)** in the circuit. The emf is defined as the energy available from a unit of charge travelling once around a loop of wire. The emf drives a current in the circuit and is the result of a changing magnetic field inducing an electric field.

The laws of electromagnetic induction (Faraday) state that the induced emf:

- is proportional to the rate of change of magnetic field and the area of the circuit;
- is proportional to the number of turns in a coil of wire Table 1.1);
- is in a direction so that it opposes the change in magnetic field which causes it (**Lenz's law**).

Table 1.1 Common equations of magnetism and electromagnetism.

Equations (if you like them)		
$B_0 = H_0 (1+x)$	B_0 is the magnetic field H_0 is magnetic intensity	This equation shows the apparent magnetization of an atom. A substance is diamagnetic when $x < 0$. A substance is paramagnetic when $x > 0$.
$\varepsilon = -N d\Phi / dt$	ε is the emf N is the number of turns in a coil $d\Phi$ is changing magnetic flux in a single loop dt is changing time	This equation shows that the amount of induced current in a coil is related to the rate of change of magnetic flux (how fast the magnetic lines of flux are crossed) and the number of turns in a coil.

Electromagnetic induction is a basic physical phenomenon of MRI, but is specifically involved in the following:

- the spinning charge of a hydrogen proton causes a magnetic field to be induced around it (see Chapter 2);
- the movement of the **net magnetization vector (NMV)** across the area of a receiver coil induces an electrical charge in the coil (see Chapter 4).

The key points of this chapter are summarized in Table 1.2.

Table 1.2 Key points.

Things to remember:
Paramagnetic substances add to (increase) the applied magnetic field.
Super-paramagnetic substances have a magnetic susceptibility that is greater than paramagnetic substances but less than that of ferromagnetic materials.
Diamagnetic substances slightly oppose (decrease) the applied magnetic field.
Diamagnetic effects appear in all substances. However, in materials that possess both diamagnetic and paramagnetic properties, the positive paramagnetic effect is greater than the negative diamagnetic effect, and so the substance appears paramagnetic.
Ferromagnetic substances are strongly attracted to, and align with, the applied magnetic field. They are permanently magnetized even when the applied field is removed.
Moving a conductor through a magnetic field induces an electrical charge in it.
Moving electrical charge in a conductor induces a magnetic field around it.