10.4.1 MAGNETISM

10.4.1.1 Magnets and Magnetic Fields

In around 600BC, Thales of Miletus noticed that lodestone (magnetite) could attract iron. Thales suggested that the lodestone possessed a soul. Many other ideas to explain the unusual behaviour of lodestone were proposed in the years that followed. Roman philosopher Lucretius (*ca.* 99 BC–*ca.* 55 BC), for example, speculated that particles emitted by the lodestone swept away the air between it and iron, thus attracting the iron via a kind of suction.

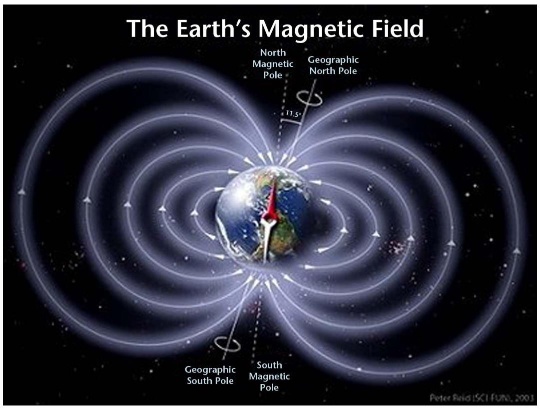
Loadstone is what we recognise today as a magnet. We may also recognise that magnets, their various shapes not withstanding, have two different ends known as **poles**—a *north pole* and a *south pole*. The poles are so-named because of the behaviour of a magnet on Earth, a property the Chinese are credited with exploiting when they invented the compass[1]. The compass, however, was used centuries earlier for other purposes. Called a “south-pointer”, the simple device featured a ladle-shaped lodestone (illustrated), the handle of which always pointed south. This earliest incarnation of the compass was more of a spiritual than navigational tool, used to guide the direction of people's lives, rather than their steps.

Compass (circa 4th Century BC)

Two magnets, when brought into proximity with one another, exert a force on each other. This magnetic force can be likened to the electric force between charged objects in that unlike poles of two magnets attract one another (as do unlike charges) and like poles repel one another (as do like charges). Electric charges differ from magnetic poles, however, in that they can be isolated, while magnetic poles cannot—the latter always exist in pairs, on either ‘end’ of a magnet.

Just as the interaction between charged objects can be described using the concept of an electric field, the concept of a **magnetic field** can be used to describe the interaction between magnets.

The direction of a magnetic field, **B**, at any location is defined as the direction in which the north pole of a compass needle points at that location. The configuration of the Earth’s magnetic field (illustrated) resembles the field that would be produced if a bar magnet were buried within the Earth. In fact, the Earth’s magnetic field is due primarily to the magnetisation of its (largely iron) molten core, and like its molten core, the Earth’s magnetic poles are constantly moving (currently at a rate of about 40km per year[2]). Nonetheless, it should be noted that the Earth’s North Magnetic Pole is actually, by definition, the *south pole* of its internal magnet,



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[1] The first written reference to compasses used in Chinese navigation, by the Chinese astronomer and mathematician Shen Kua, dates to 1086.

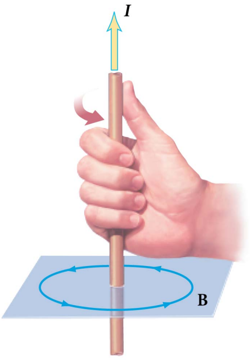
[2] http://science.nasa.gov/headlines/Y2003/29dec_magneticfield.htm

since it is this pole to which the north pole of a compass needle points, and unlike poles of magnets attract.

10.4.1.2 Electromagnetism and Magnetic Domains

While setting up materials for a lecture in 1820, Danish physicist Hans Christian Ørsted (1777–1851) also noticed that a compass needle was deflected from magnetic north when the electric current from the battery he was using was switched on and off. From this and subsequent observations he was able to show that an electric current produces a magnet field as it flows through a wire.

The direction of the magnetic field can be identified using the **right-hand rule**: if the wire is grasped in the right hand, with the thumb in the direction of the (conventional) current, **I**, as illustrated, the fingers will curl in the direction of the magnetic field, **B**.



We have seen forces resulting from interactions between masses (*gravity*) and between charges (*electric force*). We now have another force, a *magnetic force*, which results from the interaction between moving charges, or electric currents. The total force involving charges is thus called the *electromagnetic force*.

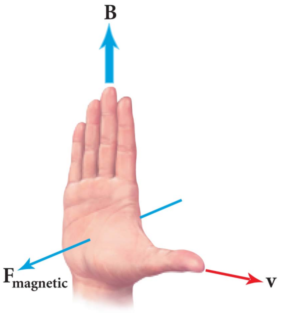
10.4.1.3 Magnetic Force

Although a stationery charged particle does not interact with a constant magnetic field, charges moving through a magnetic field experience a magnetic force. This force is at its maximum when a charge moves perpendicular to the magnetic field, decreases in value at other angles, and becomes zero when the charge is moving along field lines. The magnitude of the magnetic force ($F_{magnetic}$) on a particle moving perpendicular to a magnetic field (B) is given by the equation:

$$F_{magnetic} = qvB$$

where q is the magnitude of the charge on the particle and v is its velocity. The SI unit for magnetic field strength is the **tesla** (**T**), after the Serbian engineer Nikola Tesla (1856–1943).

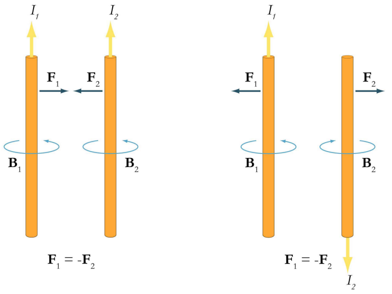
Charged Particles in a Magnetic Field



Another right-hand rule can be used to determine the direction of the magnetic force on a *positive charge*: hold the fingers in the direction of the magnetic field (**B**) with the thumb pointing in the direction of charge movement (**v**), as illustrated, and the magnetic force (**F**$_{\mathbf{magnetic}}$) will be directed out of the palm of the hand. For a *negative charge*, the force will act in the opposite direction.

On careful examination, it will thus be noted that *a charge travelling in a magnetic field will follow a circular path.*

Magnetic Force on a Current-Carrying Conductor



Since a current in a conductor creates its own magnetic field, two parallel conducting wires exert forces on each other. When the current in each wire is in the same direction, the two wires attract one another. When the currents in the two wires are in the opposite direction, the two wires repel one another.

10.4.1.4 Induced Current

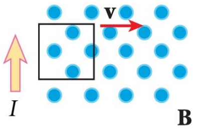
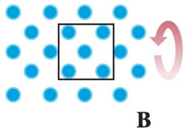
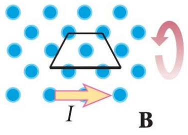
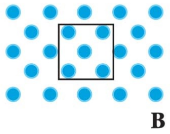
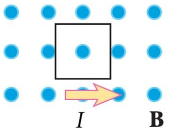
10.4.1.4.1 Magnetic Fields and Induced EMFs

Up to this point, all electric circuits that we have studied have used a battery or an electric power supply to create a potential difference within a circuit. It is also possible to *induce* a current in a circuit without the use of a battery or an electrical power supply. Just as a magnetic field can be created by a current in a circuit, a current can be induced in a circuit by moving the circuit through an external magnetic field.

The English chemist and physicist Michael Faraday (1791–1867) is generally credited with having first demonstrated this phenomenon of **electromagnetic induction** in 1831.

We saw in Section 10.4.1.3 above that a charge moving in a magnetic field experienced a magnetic force. Thus, if a conductor is moving in a magnetic field, any charges in that conductor will experience a magnetic force. Further, if the conductor is a piece of wire, and it is moved through a magnetic field that is perpendicular to the length of the wire, this magnetic force will drive the charges along the wire in the same way as the EMF from a battery. This induced EMF will remain as long as the conductor is moving relative to the magnetic field, and the direction of the induced current can be predicted using the Right Hand Rule. The magnitude of the induced EMF depends on the velocity with which the wire is moved through the magnetic field, the length of the wire, and the strength of the magnetic field.

The ways of inducing a current in a circuit are summarised in the following table[3].

Description	Before	After
Circuit is moved into or out of magnetic field (either circuit or magnet moving)		
Circuit is rotated in the magnetic field (angle between area of circuit and magnetic field changes)		
Intensity of magnetic field is varied		

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[3] Holt Physics, Ch 22, Table 22-1, p. 796

10.4.1.4.2 Characteristics of Induced Current

Lenz's Law, after the Russian physicist Heinrich Lenz (1804–1865), states that:

> *The magnetic field of the induced current opposes the change in the applied magnetic field.*

Note that the field of the induced current does not oppose the applied field but rather the *change* in the applied field. If the applied field changes, the induced field attempts to keep the total field strength constant, in accordance with the principle of conservation of energy.

Lenz's Law does not provide information on the magnitude of the induced current or the induced EMF. To calculate these, we must use Faraday's Law of Magnetic Induction, which may be expressed mathematically as:

$$EMF = -N \frac{\Delta\left[AB\left(\cos\theta\right)\right]}{\Delta t}$$

where

EMF is the average induced EMF
N is the number of loops in the circuit
A is the circuit loop area
$B(\cos\theta)$ is the magnetic field component normal to the plane of the loop

and the negative sign indicates the polarity of the induced EMF in accordance with Lenz's Law.

References

Holt Physics, Serway, R.A. and Faughn, J.S. (Holt, Rinehart and Winston, 2000) [ISBN 0-03-056544-8] Ch. 17-22

Work directly from text, with exercises:

21 Magnetism

21.1 Magnets and magnetic fields
21.2 Electromagnetism and magnetic domains
21.3 Magnetic force

22 Induction and Alternating Current

22.1 Induced current
22.2 Alternating current, generators and motors
22.3 Inductance

The Molecular Expressions™ Web site, hosted by Florida State University, contains a lot of useful educational material on electricity and magnetism:

http://micro.magnet.fsu.edu/electromag/index.html