ferromagnetic substance of samples. This motion of suspension can be observed. Figure 5.12(b) shows the situation when the domains have aligned and amalgamated to form a single 'giant' domain.

Thus, in a ferromagnetic material the field lines are highly concentrated. In non-uniform magnetic field, the sample tends to move towards the region of high field. We may wonder as to what happens when the external field is removed. In some ferromagnetic materials the magnetisation persists. Such materials are called *hard* magnetic materials or *hard ferromagnets*. Alnico, an alloy of iron, aluminium, nickel, cobalt and copper, is one such material. The naturally occurring lodestone is another. Such materials form permanent magnets to be used among other things as a compass needle. On the other hand, there is a class of ferromagnetic materials in which the magnetisation disappears on removal of the external field. Soft iron is one such material. Appropriately enough, such materials are called *soft ferromagnetic materials*. There are a number of elements, which are ferromagnetic: iron, cobalt, nickel, gadolinium, etc. The relative magnetic permeability is >1000!

The ferromagnetic property depends on temperature. At high enough temperature, a ferromagnet becomes a paramagnet. The domain structure disintegrates with temperature. This disappearance of magnetisation with temperature is gradual. It is a phase transition reminding us of the melting of a solid crystal. The temperature of transition from ferromagnetic to paramagnetism is called the *Curie temperature* T_c. Table 5.4 lists the Curie temperature of certain ferromagnets. The susceptibility above the Curie temperature, i.e., in the paramagnetic phase is described by,

$$\chi = \frac{C}{T - T_c} \quad (T > T_c) \tag{5.21}$$

Hysterisis in magnetic materials:
http://hyperphysics.phy-astr.gsu.edu/hbase/solids/hyst.html

PHYSICS

TABLE 5.4 CURIE TEMPERATURE T_c OF SOME FERROMAGNETIC MATERIALS

Material	T_c (K)
Cobalt	1394
Iron	1043
Fe_2O_3	893
Nickel	631
Gadolinium	317

EXAMPLE 5.11

Example 5.11 A domain in ferromagnetic iron is in the form of a cube of side length 1∝m. Estimate the number of iron atoms in the domain and the maximum possible dipole moment and magnetisation of the domain. The molecular mass of iron is 55 g/mole and its density is 7.9 g/cm^3. Assume that each iron atom has a dipole moment of 9.27×10^{-24} A m^2.

Solution The volume of the cubic domain is
$V = (10^{-6}\text{ m})^3 = 10^{-18}\text{ m}^3 = 10^{-12}\text{ cm}^3$
Its mass is volume × density $= 7.9\text{ g cm}^{-3} \times 10^{-12}\text{ cm}^3 = 7.9 \times 10^{-12}\text{ g}$
It is given that Avagadro number (6.023×10^{23}) of iron atoms have a mass of 55 g. Hence, the number of atoms in the domain is

$$N = \frac{7.9 \cdot 10^{-12} \cdot 6.023 \quad 10^{23}}{55}$$
$$= 8.65 \times 10^{10}\text{ atoms}$$

The maximum possible dipole moment m_{max} is achieved for the (unrealistic) case when all the atomic moments are perfectly aligned. Thus,

$$m_{max} = (8.65 \times 10^{10}) \times (9.27 \times 10^{-24})$$
$$= 8.0 \times 10^{-13}\text{ A m}^2$$

The consequent magnetisation is

$$M_{max} = m_{max}/\textit{Domain volume}$$
$$= 8.0 \times 10^{-13}\text{ Am}^2/10^{-18}\text{ m}^3$$
$$= 8.0 \times 10^5\text{ Am}^{-1}$$

EXAMPLE 5.11

The relation between **B** and **H** in ferromagnetic materials is complex. It is often not linear and it depends on the magnetic history of the sample. Figure 5.14 depicts the behaviour of the material as we take it through one cycle of magnetisation. Let the material be unmagnetised initially. We place it in a solenoid and increase the current through the solenoid. The magnetic field *B* in the material rises and saturates as depicted in the curve Oa. This behaviour represents the alignment and merger of domains until no further enhancement is possible. It is pointless to increase the current (and hence the magnetic intensity *H*) beyond this. Next, we decrease *H* and reduce it to zero. At *H* = 0, B ≠ 0. This is represented by the curve ab. The value of *B* at *H* = 0 is called *retentivity* or *remanence*. In Fig. 5.14, $B_R \sim 1.2$ T, where the subscript *R* denotes retentivity. The domains are not completely randomised even though the external driving field has been removed. Next, the current in the solenoid is reversed and slowly increased. Certain domains are flipped until the net field inside stands nullified. This is represented by the curve bc. The value of *H* at c is called *coercivity*. In Fig. 5.14 $H_c \sim -90\text{ A m}^{-1}$. As the reversed current is increased in magnitude, we once again obtain saturation. The curve cd depicts this. The saturated magnetic field $B_s \sim 1.5$ T. Next, the current is reduced (curve de) and reversed (curve ea). The cycle repeats itself. Note that the curve Oa does not retrace itself as *H* is reduced. For a given value of *H*, *B* is not unique but depends on previous history of the sample. This phenomenon is called *hysterisis*. The word *hysterisis* means *lagging behind* (and not 'history').

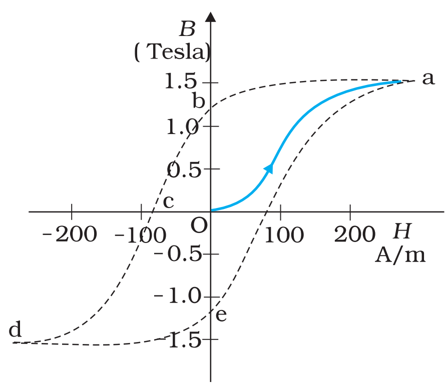

FIGURE 5.14 The magnetic hysteresis loop is the B-H curve for ferromagnetic materials.

5.7 Permanent Magnets and Electromagnets

Substances which at room temperature retain their ferromagnetic property for a long period of time are called *permanent magnets*. Permanent

FIGURE 5.15 A blacksmith forging a permanent magnet by striking a red-hot rod of iron kept in the north-south direction with a hammer. The sketch is recreated from an illustration in De Magnete, a work published in 1600 and authored by William Gilbert, the court physician to Queen Elizabeth of England.

magnets can be made in a variety of ways. One can hold an iron rod in the north-south direction and hammer it repeatedly. The method is illustrated in Fig. 5.15. The illustration is from a 400 year old book to emphasise that the making of permanent magnets is an old *art*. One can also hold a steel rod and stroke it with one end of a bar magnet a large number of times, always in the same sense to make a permanent magnet.

An efficient way to make a permanent magnet is to place a ferromagnetic rod in a solenoid and pass a current. The magnetic field of the solenoid magnetises the rod.

The hysteresis curve (Fig. 5.14) allows us to select suitable materials for permanent magnets. The material should have high retentivity so that the magnet is strong and high coercivity so that the magnetisation is not erased by stray magnetic fields, temperature fluctuations or minor mechanical damage. Further, the material should have a high permeability. Steel is one-favoured choice. It has a slightly smaller retentivity than soft iron but this is outweighed by the much smaller coercivity of soft iron. Other suitable materials for permanent magnets are alnico, cobalt steel and ticonal.

Core of electromagnets are made of ferromagnetic materials which have high permeability and low retentivity. Soft iron is a suitable material for electromagnets. On placing a soft iron rod in a solenoid and passing a current, we increase the magnetism of the solenoid by a thousand fold. When we switch off the solenoid current, the magnetism is effectively switched off since the soft iron core has a low retentivity. The arrangement is shown in Fig. 5.16.

Indiaís Magnetic Field:
http://iigs.iigm.res.in

PHYSICS

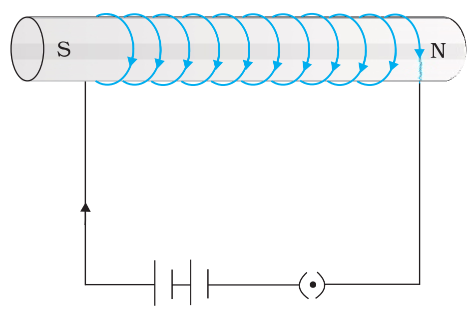

FIGURE 5.16 A soft iron core in solenoid acts as an electromagnet.

In certain applications, the material goes through an ac cycle of magnetisation for a long period. This is the case in transformer cores and telephone diaphragms. The hysteresis curve of such materials must be narrow. The energy dissipated and the heating will consequently be small. The material must have a high resistivity to lower eddy current losses. You will study about eddy currents in Chapter 6.

Electromagnets are used in electric bells, loudspeakers and telephone diaphragms. Giant electromagnets are used in cranes to lift machinery, and bulk quantities of iron and steel.

Mapping India's magnetic field

Because of its practical application in prospecting, communication, and navigation, the magnetic field of the earth is mapped by most nations with an accuracy comparable to geographical mapping. In India over a dozen observatories exist, extending from Trivandrum (now Thrivuvananthapuram) in the south to Gulmarg in the north. These observatories work under the aegis of the Indian Institute of Geomagnetism (IIG), in Colaba, Mumbai. The IIG grew out of the Colaba and Alibag observatories and was formally established in 1971. The IIG monitors (via its nation-wide observatories), the geomagnetic fields and fluctuations on land, and under the ocean and in space. Its services are used by the Oil and Natural Gas Corporation Ltd. (ONGC), the National Institute of Oceanography (NIO) and the Indian Space Research Organisation (ISRO). It is a part of the world-wide network which ceaselessly updates the geomagnetic data. Now India has a permanent station called Gangotri.

SUMMARY

1. The science of magnetism is old. It has been known since ancient times that magnetic materials tend to point in the north-south direction; like magnetic poles repel and unlike ones attract; and cutting a bar magnet in two leads to two smaller magnets. Magnetic poles cannot be isolated.
2. When a bar magnet of dipole moment **m** is placed in a uniform magnetic field **B**,
   (a) the force on it is zero,
   (b) the torque on it is **m × B**,
   (c) its potential energy is **–m·B**, where we choose the zero of energy at the orientation when **m** is perpendicular to **B**.
3. Consider a bar magnet of size *l* and magnetic moment **m**, at a distance *r* from its mid-point, where *r* >>*l*, the magnetic field **B** due to this bar is,

$$\mathbf{B} = \frac{\mu_0 \mathbf{m}}{2\pi r^3} \quad \text{(along axis)}$$

$$= -\frac{\mu_0 \mathbf{m}}{4\pi r^3} \quad \text{(along equator)}$$

4. Gauss's law for magnetism states that the net magnetic flux through any closed surface is zero

$$\phi_B = \sum_{\substack{\text{all area} \\ \text{elements } \Delta\mathbf{S}}} \mathbf{B}\cdot\Delta\mathbf{S} = 0$$

5. The earth's magnetic field resembles that of a (hypothetical) magnetic dipole located at the centre of the earth. The pole near the geographic north pole of the earth is called the north magnetic pole. Similarly, the pole near the geographic south pole is called the south magnetic pole. This dipole is aligned making a small angle with the rotation axis of the earth. The magnitude of the field on the earth's surface $\approx 4 \times 10^{-5}$ T.

6. Three quantities are needed to specify the magnetic field of the earth on its surface – the horizontal component, the magnetic declination, and the magnetic dip. These are known as the elements of the earth's magnetic field.
7. Consider a material placed in an external magnetic field $\mathbf{B}_0$. The magnetic intensity is defined as,
$$\mathbf{H} = \frac{\mathbf{B}_0}{\propto_0}$$
The magnetisation **M** of the material is its dipole moment per unit volume. The magnetic field **B** in the material is,
$$\mathbf{B} = \propto_0 (\mathbf{H} + \mathbf{M})$$
8. For a linear material $\mathbf{M} = \chi\,\mathbf{H}$. So that $\mathbf{B} = \propto \mathbf{H}$ and χ is called the magnetic susceptibility of the material. The three quantities, χ, the relative magnetic permeability $\propto_r$, and the magnetic permeability $\propto$ are related as follows:
$$\propto = \propto_0 \propto_r$$
$$\propto_r = 1 + \chi$$
9. Magnetic materials are broadly classified as: diamagnetic, paramagnetic, and ferromagnetic. For diamagnetic materials χ is negative and small and for paramagnetic materials it is positive and small. Ferromagnetic materials have large χ and are characterised by non-linear relation between **B** and **H**. They show the property of hysteresis.
10. Substances, which at room temperature, retain their ferromagnetic property for a long period of time are called permanent magnets.

Physical quantity	Symbol	Nature	Dimensions	Units	Remarks
Permeability of free space	$\propto_0$	Scalar	$[MLT^{-2}\ A^{-2}]$	$T\ m\ A^{-1}$	$\propto_0/4\pi = 10^{-7}$
Magnetic field, Magnetic induction, Magnetic flux density	**B**	Vector	$[MT^{-2}\ A^{-1}]$	T (tesla)	10^4 G (gauss) = 1 T
Magnetic moment	**m**	Vector	$[L^{-2}\ A]$	$A\ m^2$	
Magnetic flux	ϕ_B	Scalar	$[ML^2T^{-2}\ A^{-1}]$	W (weber)	$W = T\ m^2$
Magnetisation	**M**	Vector	$[L^{-1}\ A]$	$A\ m^{-1}$	$\frac{\text{Magnetic moment}}{\text{Volume}}$
Magnetic intensity Magnetic field strength	**H**	Vector	$[L^{-1}\ A]$	$A\ m^{-1}$	$\mathbf{B} = \propto_0 (\mathbf{H} + \mathbf{M})$
Magnetic susceptibility	χ	Scalar	-	-	$\mathbf{M} = \chi\mathbf{H}$
Relative magnetic permeability	$\propto_r$	Scalar	-	-	$\mathbf{B} = \propto_0 \propto_r \mathbf{H}$
Magnetic permeability	$\propto$	Scalar	$[MLT^{-2}\ A^{-2}]$	$T\ m\ A^{-1}$ $N\ A^{-2}$	$\propto = \propto_0 \propto_r$ $\mathbf{B} = \propto \mathbf{H}$