Part I
Introduction to Magnetism and Magnetic Materials
The book begins with an exposition of the interesting history of magnetism and magnetic materials. This is followed by a short chapter discussing the role of magnetism and magnetic materials in modern society and current technological applications of magnetic materials and devices. This second chapter highlights why magnetism is considered to be more of an applied or experimental science rather than a theoretical one.
A Short History of Magnetism and Magnetic Materials

The magnetite iron ore FeO - Fe$_2$O$_3$ (or Fe$_3$O$_4$), famously known as lodestone, is the first known natural magnet. Folklore is that roughly around 2500 BC a Greek shepherd was tending his sheep in a region of ancient Greece called Magnesia (now in modern Turkey), and the nails that held his shoe together were stuck to the rock he was standing on. There were more such ancient stories about iron parts being pulled out from hulls of the ships sailing past the islands in the south Pacific and ones about the disarming and immobilizing of knights in their iron armor. Depending on the time and places where Fe$_3$O$_4$ or magnetite ore was found, it was variously known as the Magnesia stone, lodestone, the stone of Lydia, l’aimant in France, chumbak in India, or ts’u she in China. The modern name magnet is possibly derived from early lodestones found in the ancient Greek region of Magnesia.

The chronicled history of magnetism dates back to 600 BC. Lodestone’s magnetic properties were studied and documented by the famous Greek philosopher Thales of Miletus (Fig. 1.1) in 600 BC [1]. Around the same period, the magnetic properties of lodestone were known in India, and the well-known ancient physician sage Sushruta (see Fig. 1.1) applied it to draw out metal splinters from bodies of injured soldiers [2]. However, Chinese writings dating back to 4000 BC mention magnetite, and indicate the possibility that original discoveries of magnetism might have taken place in China [3]. The Chinese were the first to notice that lodestone would orient itself to point north if not hindered by gravity and friction. The early Chinese compasses, however, were used in fortune-telling through the interpretation of lines and geographic alignments as symbols of the divine. These were also used for creating harmony in a room or building with the alignment of various features to different
Figure 1.1 Greek philosopher Thales of Miletus and Indian sage physician Sushruta. (Source: https://commons.wikimedia.org/)

Figure 1.2 Ladle shaped Chinese south pointer compass. (Source: CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=553022)

compass points. The first navigational lodestone compasses emerged from China. They had a unique design with the lodestone being shaped as a ladle (Fig. 1.2). The lodestone ladle sat in the center of a bronze or copper plate/disc. These compasses rotated freely when pushed and usually came to rest with the handle part of the ladle pointing south and so were known as south pointers. The copper/bronze base would be inscribed with cardinal direction points and other important symbols.

An important discovery (attributed to Zheng Gongliang in 1064) was that iron acquired a thermoremanent magnetization when quenched from high temperature.
FIGURE 1.3 Medieval navigational compass. (Source: https://www.freepnglogos.com/pics/compass)

red hot conditions [4]. The first artificial permanent magnets were the steel needles thus magnetized in the Earth’s field. These needles aligned themselves with the Earth’s field when suitably suspended or floated; that eventually led to their use as navigational compasses especially for sea voyages. Such compasses were reinvented in Europe a century later and played a very important role in the great voyages of discovery. Fig. 1.3 shows a medieval navigational compass.

A systematic study of magnetism was started in the sixteenth century by an English physicist, William Gilbert of Colchester (Fig. 1.4), who also happened to be the personal physician of Queen Elizabeth I of England. Gilbert performed experiments with a magnetic needle placed on the surface of a lodestone sphere and conjectured that the Earth is a large spherical magnet. Within this framework, the north-south pointing property of a compass needle could be conceptualized with the attraction of unlike poles of magnets. He also investigated the temperature-dependent magnetic properties of iron and observed that iron was no more attracted to a magnet when it became red hot. Gilbert also could distinguish clearly between static electricity and magnetism and documented all his investigations of magnetic and static electricity phenomena in a monograph, *De Magnete*, first published in London in 1600. This monograph is possibly the first printed textbook in any branch of modern physics [3].

Significant progress was made during the 1700s in making artificial magnets from iron bars and steel. Another important event was the invention of the horseshoe magnet in 1743 by Daniel Bernoulli (Fig. 1.4). This was to become the most classic shape of the magnet, and remains as an icon of magnetism even today. However, the
next major development in the understanding of the subject took place only in the eighteenth century when Charles-Augustin de Coulomb (Fig. 1.4) experimentally found the inverse square force law, namely the Coulomb law, between electrical charges as well as magnetic poles. Subsequently, Simeon Denis Poisson (Fig. 1.4) and Carl Friedrich Gauss (Fig. 1.5) formulated an elegant mathematical theory for Coulomb’s experimental findings. In 1820 Danish physicist Hans Christian Oersted (Fig. 1.5) discovered that a wire carrying an electrical current can deflect a magnetic needle placed nearby. An explanation for this discovery was put forward by the French scientist Andre-Marie Ampere (Fig. 1.5) in terms of a magnetic force around a current-carrying wire. This idea led to a law, which is now known as the Ampere law that was further formulated in a mathematical form by James Clerk Maxwell (Fig. 1.6). Ampere also carried out further experiments on the magnetic effects of electric currents, including measurements of forces between current-carrying wires.

The next important development in the field of magnetism was due to Michael Faraday (Fig. 1.5), when in 1831 he discovered the law of electromagnetic induction. He put two coils of insulated copper wire around a thick iron ring on two opposite sides, and connected one of the coils to a galvanometer and the other to a battery through a switch. Faraday observed sudden deflection in the galvanometer when the switch was closed or opened. This observation marked the discovery of the phenomenon of electromagnetic induction. Subsequently, Faraday also found that a current could be induced in a coil with the movement of a permanent magnet.
near the coil. He carried forward the studies of Oersted and Ampere and introduced the revolutionary concept of magnetic and electric fields. Faraday also discovered diamagnetism and paramagnetism in substances like bismuth and oxygen, and observed that diamagnetic substances were repelled from stronger magnetic fields while paramagnetic substances were attracted towards these.

James Clerk Maxwell (Fig. 1.6) expressed experimental findings of Faraday in elegant mathematical language in the form of the now-famous Maxwell equations. Not only Faraday’s but the findings of Coulomb, Oersted, Ampere, and Poisson too could now be expressed by Maxwell equations. That subsequently led to further developments in magnetism and ultimately a technological revolution. Lorentz introduced an additional equation for the force on a particle with charge $q$ moving with velocity $v$ and subjected to a combined electric and magnetic field.

The experimental findings of Michael Faraday on paramagnetic and diamagnetic materials were advanced further by Pierre Curie (Fig. 1.6). He investigated the possibility of phase transitions between various kinds of magnetism in a given material by performing a thorough study of magnetic properties of some twenty substances [5]. His studies led to three important discoveries: (1) diamagnetism is generally approximately temperature-independent; (2) paramagnetism in various magnetic materials is temperature-dependent and magnetic susceptibility is inversely proportional to temperature; this is now famously known as the Curie law; (3) ferromagnetism disappears when the temperature is raised above a critical point called the Curie temperature. Paul Langevin (Fig. 1.6) provided the first microscopic mathematical theory of the behavior of diamagnetic and paramagnetic substances.
Langevin deduced the correct temperature dependence of magnetization of a paramagnetic sample with an ad-hoc assumption of a tiny magnetic moment associated with each atom of the sample and the inclusion of the thermal agitation of magnetic moments. Langevin’s theory was generalized further by Pierre Weiss (Fig. 1.6) to explain ferromagnetism by introducing the important concept of mean molecular field. Explanation of ferromagnetism by the theory of Weiss, however, was only partial and a complete understanding had to wait for a quantum mechanical explanation.

George Uhlenbeck and Samuel Goudsmit (Fig. 1.7) in 1925 discovered the intrinsic spin of the electron, which is quantized in such a manner that it can have just two possible orientations, up and down, in an applied magnetic field. The intrinsic magnetic moment of the electron the Bohr magneton: $\mu_B = 9.274 \times 10^{-24}\text{Am}^2$ or $9.274 \times 10^{-24}\text{JT}^{-1}$ originates from the spin, and the magnetic properties of solids originate from the magnetic moments of their atomic electrons. Werner Heisenberg (Fig. 1.7) in 1929 showed that the Weiss molecular field in
Ferromagnets arose from two interconnected effects, namely the quantum mechanics of the exclusion principle introduced by Wolfgang Pauli (Fig. 1.7) and electrostatic repulsion between two electrons. The core idea is that a quantum mechanical exchange interaction causes the ferromagnetic alignment of tiny atomic magnetic moments. Exchange interaction in ferromagnets has positive values, but it can also have negative values leading to antiparallel rather than parallel alignment of magnetic moments. Louis Néel (Fig. 1.7) in 1936 and 1948 pointed out the possibility of such antiferromagnetism and ferrimagnetism, depending on the crystal structure of the material. The archetypal natural magnetic material magnetite Fe$_3$O$_4$ is a ferrimagnet.

On the materials and technology front, in 1750 an English physicist and astronomer, John Michell, developed a method of making magnets from soft iron and hardened steel, and the latter retained magnetization for a considerably longer time. Another technical landmark was William Sturgeon’s invention of the iron-cored
electromagnet in 1824. The electromagnet had a horseshoe-shaped core, which was magnetized by the magnetic field produced with the flow of electric current in the magnet windings [4]. The era of modern technology, however, started in the 1930s when it was found that the carbon-free iron-rich ternary alloy with 25% nickel and 10% aluminum was a ferromagnet with a relatively high magnetic coercivity, and which did not require hardening. The properties of these magnets were improved further during the next 50 years by substituting part of the iron with cobalt and adding copper and titanium. The magnets were also prepared by sintering powdered alloys, and also by powder bonding with plastic and then subjecting to pressure. These magnets are known as Alnico magnets, and they have been widely used in military as well as civil electronic applications such as automotive and aircraft sensor applications.

In the 1950s ceramic materials barium ferrite oxides (BaFe$_{12}$O$_{19}$) and strontium ferrite oxides (SrFe$_{12}$O$_{19}$), better known as ferrite magnets, were introduced. These are ferrimagnets with both ferromagnetic and antiferromagnetic coupling between atomic moments with magnetic interaction depending on the specific crystallographic position of iron ions. Despite their poorer service parameters (brittleness, low magnetization value at room temperature) compared to Alnico magnets, ferrite magnets have the commercial and industrial advantage due to their low cost and chemical inertness and also because they are easy to process.

In the mid-1960s new permanent magnets were prepared with the alloying of rare earth elements with 3d-transition metals (Fe, Ni, Co). The examples of such permanent magnets are SmCo$_5$, Sm$_2$Co$_{17}$ and Sm-Fe-N magnets, especially Sm$_2$Fe$_{17}$N$_3$. Research in this field eventually led to the development of Nd-Fe-B magnets in the mid-1980s. It may be noted that forming perfect Nd$_2$Fe$_{14}$B and Sm$_2$Fe$_{17}$N$_3$ phases is a difficult if not impossible task. Thus the focus of research moved towards improving the microstructure of the materials. Magnets of nanocrystalline structure, nanocomposite, and anisotropic diphase nanocrystalline magnets were produced. Fig. 1.8 shows the evolution of permanent magnetic materials since the early twentieth century.

It may be noted here that while fundamental understanding of magnet science was definitely of help, it was not necessarily a prerequisite for metallurgical and initial technological progress. The progression from the poorly distinguished soft and hard magnetic steels in the early twentieth century to the wealth of different magnetic materials available today are more due to metallurgy and solid-state and structural chemistry. Quantum mechanics, however, started contributing significantly to the development of magnetic materials involving rare earth and transition metals [4]. The interplay between science and technology over the last century, especially from the early 1950s, led to an immense expansion in the applications of magnetic materials, more so during the last five decades. Much of