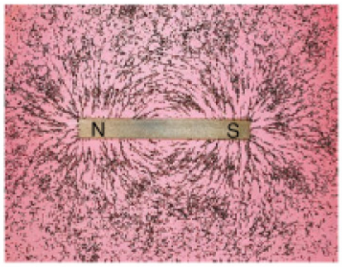


FIGURE 20–41 Iron filings line up along magnetic field lines due to a permanent magnet.

acquire aligned domains and align themselves to reveal the shape of the magnetic field, Fig. 20–41. See also this Chapter's opening photograph p. 554.

An iron magnet can remain magnetized for a long time, and is referred to as a "permanent magnet." But if you drop a magnet on the floor or strike it with a hammer, you can jar the domains into randomness and the magnet loses some or all of its magnetism. Heating a permanent magnet can also cause loss of magnetism, for raising the temperature increases the random thermal motion of atoms, which tends to randomize the domains. Above a certain temperature known as the **Curie temperature** (1043 K for iron), a magnet cannot be made at all.

The striking similarity between the fields produced by a bar magnet and by a loop of electric current or a solenoid (Figs. 20–4b, 20–9, and 20–30) offers a clue that perhaps the magnetic field produced by a current may have something to do with ferromagnetism. According to modern atomic theory, the atoms that make up any material can be roughly visualized as having electrons that orbit around a central nucleus. The electrons are charged, and so constitute an electric current and therefore produce a magnetic field. Electrons themselves produce an additional magnetic field, almost as if they and their electric charge were spinning about their own axes. It is the magnetic field due to electron *spin*[†] that is believed to produce ferromagnetism in most ferromagnetic materials.

CAUTION

$\vec{\mathbf{B}}$ lines form closed loops, $\vec{\mathbf{E}}$ start on ⊕ and end on ⊖

It is believed today that *all* magnetic fields are caused by electric currents. This means that magnetic field lines always form closed loops, unlike electric field lines which begin on positive charges and end on negative charges.

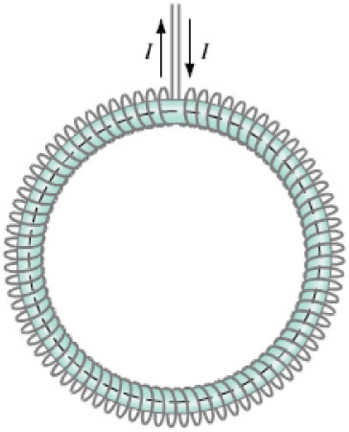
* Magnetic Permeability

If a piece of iron is placed inside a solenoid to form an electromagnet, the magnetic field increases greatly over that produced by the current in the solenoid coils alone. The total magnetic field $\vec{\mathbf{B}}$ is then the sum of two terms, $\vec{\mathbf{B}} = \vec{\mathbf{B}}_0 + \vec{\mathbf{B}}_{\mathrm{M}}$ where $\vec{\mathbf{B}}_0$ is the field due to the current in the wire and $\vec{\mathbf{B}}_{\mathrm{M}}$ is the additional field due to the iron (or other magnetic material inserted instead). Often $B_{\mathrm{M}} \gg B_0$. The total field can also be written by replacing the constant μ_0 in Eq. 20–8 ($B = \mu_0 NI/l$ for a solenoid) by the **magnetic permeability** μ, which is characteristic of the magnetic material inside the coil. Then $B = \mu NI/l$. For ferromagnetic materials, μ is much greater than μ_0. For all other materials, its value is very close to μ_0.[‡] The value of μ, however, is not constant for ferromagnetic materials; it depends on the strength of the "external" field B_0, as the following experiment shows.

* Hysteresis

To make measurements on magnetic materials, a toroid is used, which is essentially a long solenoid bent into the shape of a donut (Fig. 20–42), so practically all the lines of $\vec{\mathbf{B}}$ remain within the toroid. Consider a toroid with an iron core that is initially unmagnetized and there is no current in the wire loops. Then the current I is slowly increased. The total magnetic field B, which is the sum of the field due to the current alone (B_0) plus the field due to the iron, also increases, but follows the curved line shown in the graph of

FIGURE 20–42 Iron-core toroid.



[†] The name "spin" comes from the early suggestion that the additional magnetic field arises from the electron "spinning" on its axis (as well as "orbiting" the nucleus) to produce the extra field. However, this view of a spinning electron is oversimplified and not valid (see Chapter 28).

[‡] All materials are slightly magnetic. Nonferromagnetic materials fall into two principal classes: (1) **paramagnetic** materials consist of atoms that have a net magnetic dipole moment which can align slightly with an external field, just as the galvanometer coil in Fig. 20–33 experiences a torque that tends to align it; (2) **diamagnetic** materials have atoms with no net dipole moment, but in the presence of an external field electrons revolving in one direction increase in speed slightly whereas electrons revolving in the opposite direction are reduced in speed; the result is a slight net magnetic effect that opposes the external field.