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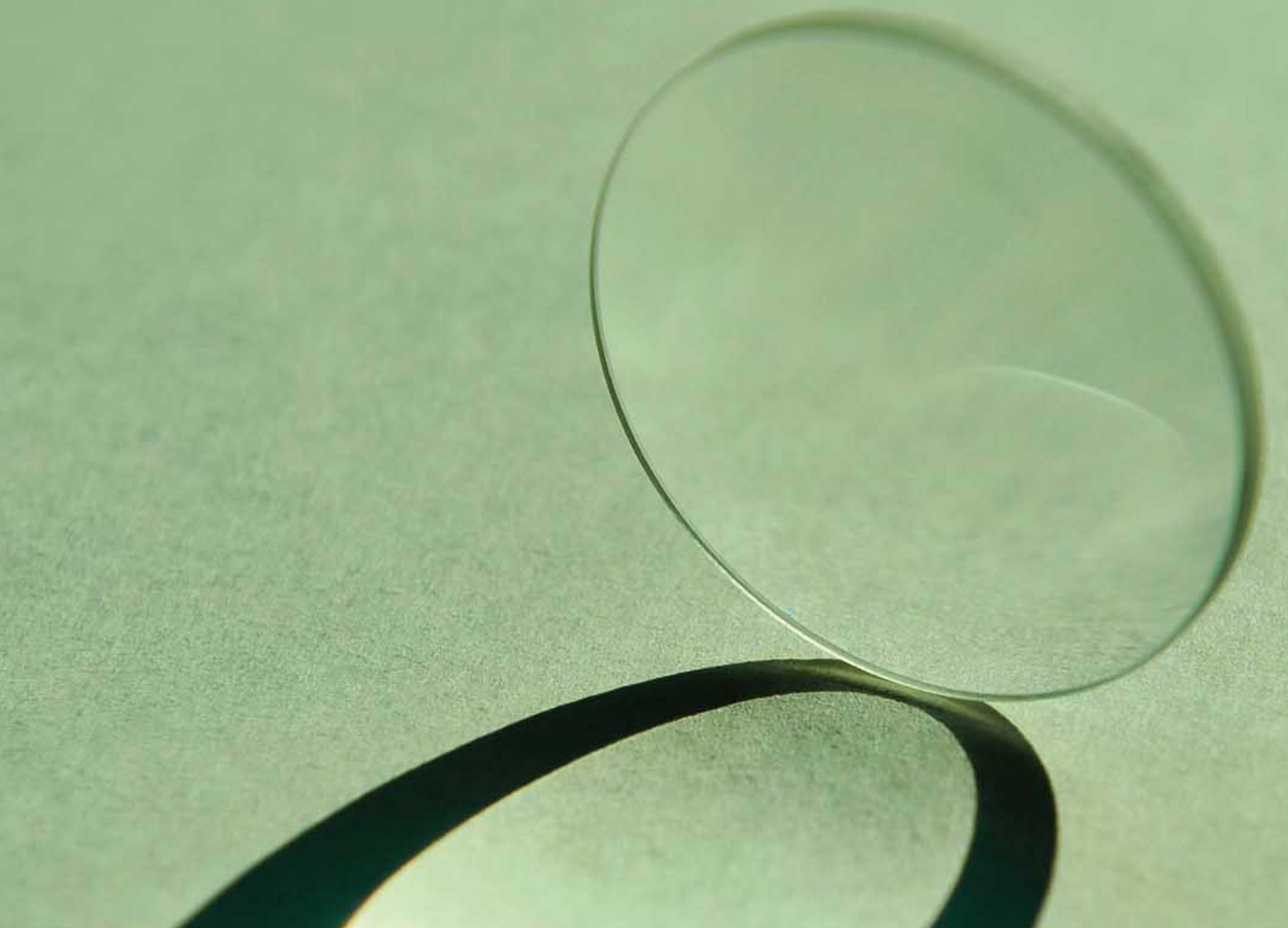

Essential University Physics

Volume 2

FOURTH EDITION

Richard Wolfson

VOLUME TWO

Chapters 20–39

Essential University Physics

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GLOBAL EDITION

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Pearson

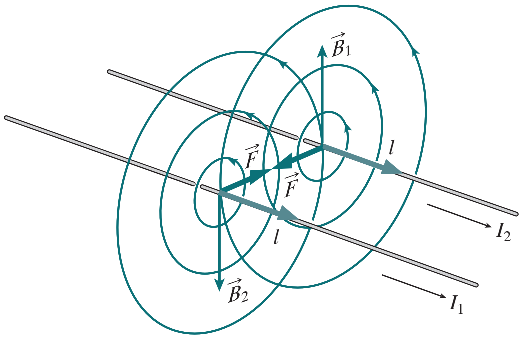


FIGURE 26.20 The magnetic force between parallel currents in the same direction is attractive.

d apart, so the field of wire 1 at the location of wire 2 follows from Equation 26.10: $B_1 = \mu_0 I_1/2\pi d$. The field is perpendicular to wire 2, so the force on a length l of wire 2 is

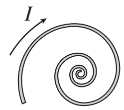
$$F_2 = I_2 l B_1 = \frac{\mu_0 I_1 I_2 l}{2\pi d} \quad \text{(magnetic force between two wires)} \qquad (26.11)$$

Figure 26.20 shows that the direction of this force is toward wire 1, so the parallel currents *attract*. Analyzing the force on wire 1 from wire 2 amounts to interchanging the subscripts 1 and 2, giving an attractive force of the same magnitude. Reversing one of the currents would change the signs of both forces, showing that antiparallel currents *repel*.

The force between nearby conductors can be quite large, so engineers who design high-strength electromagnets must provide enough physical support to withstand the magnetic force (Problem 85 considers this situation). The hum you often hear around electrical equipment comes from the mechanical vibration of nearby conductors in transformers and other devices as they respond to the changing force associated with 50-Hz alternating current.

GOT IT?

26.5 A flexible wire is wound into a flat spiral as shown in the figure. (1) If a current flows in the direction shown, will the coil (a) tighten or (b) become looser? (2) Does your answer depend on the current direction? *Note:* The current enters and leaves the coil through wires (not shown) at each end, perpendicular to the page.



26.6 Magnetic Dipoles

LO 26.6 *Describe magnetic dipoles and their interactions with magnetic fields.*

The current loop of Example 26.4 shows the essential characteristic of all steady-state currents—namely, a closed loop with current everywhere the same. Equation 26.9 gives the field on the loop axis: $B = \mu_0 I a^2/2(x^2 + a^2)^{3/2}$. For $x \gg a$ we can ignore a^2 compared with x^2 in the denominator, giving $B \simeq \mu_0 I a^2/2x^3$. Multiply both sides by 2π to get $B \simeq 2\mu_0 IA/4\pi x^3$, where A is the loop area. Compare this result with the field on the axis of an *electric* dipole, Equation 20.6b: Both show the inverse-cube dependence of the dipole field, and both involve fundamental constants from the Coulomb and Biot–Savart laws that relate fields and their sources. Where the electric-field expression contains the electric dipole moment p, the product of charge and separation, the magnetic-field expression contains IA, the product of the loop current and loop area. We identify IA as the magnitude, μ, of the current loop's **magnetic dipole moment**. Then the on-axis magnetic dipole field becomes

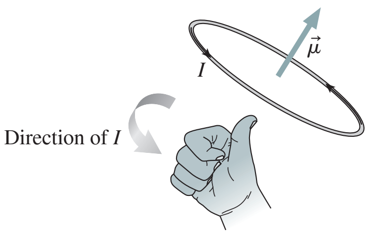


FIGURE 26.21 Finding the direction of a current loop's magnetic dipole moment.

$$B = \frac{\mu_0}{2\pi}\frac{\mu}{x^3} \quad \text{(on-axis field, magnetic dipole)} \qquad (26.12)$$

The magnetic dipole moment is a vector whose direction follows from the right-hand rule shown in Fig. 26.21. If we describe the loop by a vector of magnitude A whose direction is perpendicular to the loop as shown in Fig. 26.21, then we can write the magnetic dipole moment as $\vec{\mu} = I\vec{A}$. Practical current loops often have multiple turns; since each carries the same current, an N-turn loop has effective current NI, so its dipole moment becomes

$$\vec{\mu} = NI\vec{A} \quad \left(\begin{array}{c}\text{magnetic dipole moment,}\\ N\text{-turn current loop}\end{array}\right) \qquad (26.13)$$

$\vec{\mu}$ is the magnetic dipole moment of any current loop.

I is the current in the loop.

For loop made from a coil of wire, N is the number of turns.

$\vec{A}$ is a vector perpendicular to the loop, whose magnitude is the loop area.

Although we've found the magnetic field for a current loop only on the loop axis, a more elaborate calculation shows that the magnetic field anywhere far from the loop has exactly the same configuration as the electric field far from an electric dipole. And although we developed the magnetic dipole moment for a circular loop, Equation 26.13 in fact gives the dipole moment of *any* closed loop of current. We conclude that **any current loop constitutes a magnetic dipole**, and that far from the loop, its field will be that of a dipole. Electric and magnetic dipoles are analogous: Both have the same field configuration and mathematical form far from their sources (Fig. 26.22), and both are characterized by their respective dipole moments. But their fields aren't the same. One is an electric field, its origin in static electric charge; the other is a magnetic field, its origin in *moving* electric charge—specifically, charge moving in a closed loop. And the similarity in field configurations holds only at large distances; as Fig. 26.22 shows, the fields near electric and magnetic dipoles are very different, reflecting the different structures that give rise to each.

Current loops are ubiquitous, and so are dipole magnetic fields. Multiple turns of current-carrying wire produce the strong magnetic fields of electromagnets, and superconducting loops provide the fields in MRI scanners. At the atomic level, orbiting and spinning electrons constitute miniature magnetic dipoles. Even planets and stars have magnetic dipole fields.

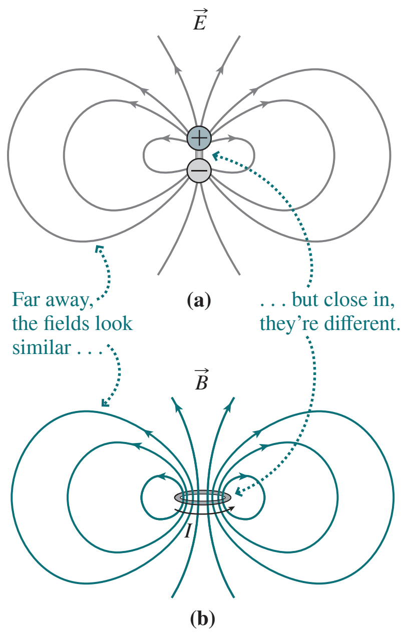
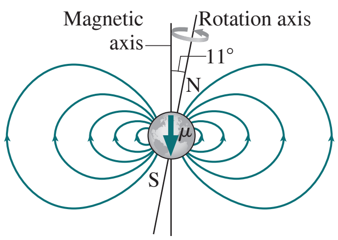


FIGURE 26.22 (a) The electric field of an electric dipole and (b) the magnetic field of a current loop. Far from their sources, both have the shape and the $1/r^3$ dependence of the dipole field.

APPLICATION Magnetic Fields of Earth and Sun

Many astrophysical objects have magnetic fields resulting from the interaction of conducting fluids with the objects' rotation. Earth's field arises in its liquid-iron outer core, where convective flows work with Earth's rotation to produce electric currents. The figure shows that Earth's field approximates that of a dipole; the magnitude of the dipole moment is approximately $\mu = 8.0\times10^{22}\ \mathrm{A\cdot m^2}$. The direction of the dipole moment vector differs from that of Earth's rotation axis, which accounts for the difference between magnetic and true north. Earth's field reverses roughly every million years, and geologists track seafloor spreading from the resulting magnetization in rocks. Farther out, Earth's magnetic field traps high-energy particles and thus protects us from dangerous radiation. You can see from the figure that magnetic field lines concentrate toward the polar regions, which is why energetic particles tend to enter Earth's atmosphere near the poles, making the aurora a high-latitude phenomenon (recall Fig. 26.10).

The Sun's gaseous nature makes its magnetic field much more dynamic, and magnetism is the dominant force in its hot, electrically conducting atmosphere. The Sun's field reverses approximately every 11 years, coinciding with the rise and fall of sunspots—regions of intense magnetic field that are often sources of violent outbursts.



Dipoles and Monopoles

Atoms, molecules, and radio antennas are among many structures that behave as *electric* dipoles. In all these, separation of positive and negative electric charge gives rise to the dipole. Magnetism is different. No one has ever found an isolated magnetic north or south pole analogous to an electric charge. Electromagnetic theory doesn't rule out such **magnetic monopoles**, and indeed some theories suggest that monopoles might have formed in the Big Bang. But they've never been found. All magnetic fields we've ever seen come from moving *electric* charge. As you'll see in Section 26.7, that includes the fields of permanent magnets. Because steady currents form closed loops, the simplest magnetic entity is the dipole.

Electric field lines generally begin or end on electric charges. But there aren't any "magnetic charges"—magnetic monopoles. Magnetic field lines don't begin or end, but form closed loops encircling the moving electric charges that are their sources. In Chapter 21 we developed Gauss's law to quantify the statement that the number of electric field lines emerging from any closed surface depends only on the charge enclosed. Because there's no magnetic charge, the net number of magnetic field lines emerging from any closed surface is always zero. Therefore the **magnetic flux** $\oint \vec{B} \cdot d\vec{A}$ through any closed surface must also be zero. Thus **Gauss's law for magnetism** is

$$\oint \vec{B} \cdot d\vec{A} = 0 \qquad \text{(Gauss's law for magnetism)} \tag{26.14}$$

The circle designates a *closed* surface.
This is the magnetic flux through a closed surface.
No isolated magnetic poles have ever been found, so the right-hand side is zero.
$\vec{B}$ is the magnetic field on the surface.
$d\vec{A}$ is an vector perpendicular to the surface, whose magnitude dA is the area of an infinitesimal patch of the surface.

Like Gauss's law for electricity, Equation 26.14 is one of the four fundamental laws that govern all electromagnetic phenomena in the universe. We'll meet the remaining two laws shortly. Although Gauss's law for magnetism has zero on its right side, it's not devoid of content; rather, it says that all magnetic fields are configured so that their field lines have no beginnings or endings.

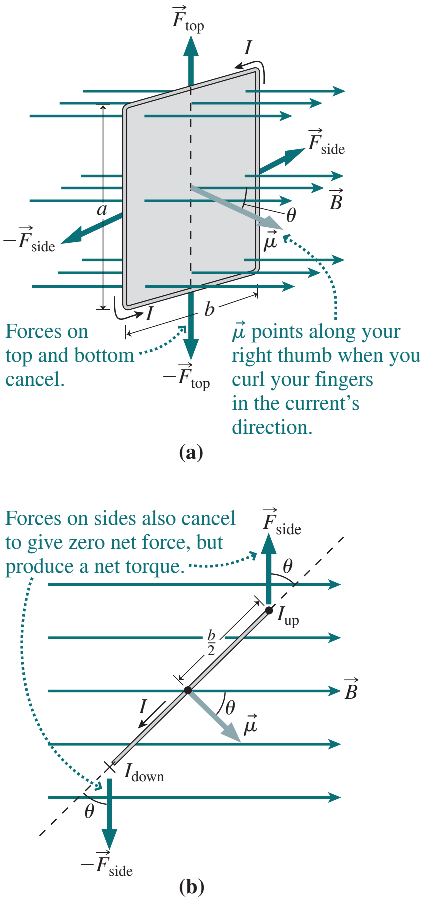
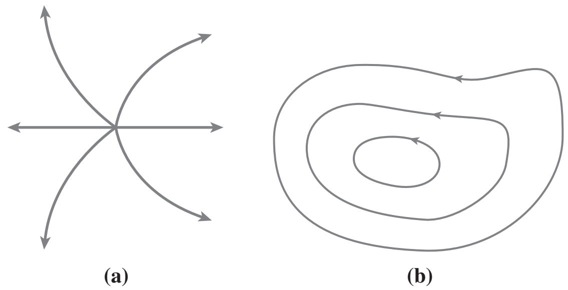


FIGURE 26.23 (a) A rectangular current loop in a uniform magnetic field. (b) Top view of the loop, showing that magnetic forces on the vertical sides result in a net torque.

GOT IT? **26.6** The figure shows two fields. Which could be a magnetic field?



The Torque on a Magnetic Dipole

In Section 20.5 we found that an electric dipole $\vec{p}$ in a uniform electric field $\vec{E}$ experiences a torque $\vec{\tau} = \vec{p} \times \vec{E}$; in a nonuniform field there's a net force as well. The same is true for a magnetic dipole in a magnetic field, as you can see by considering the rectangular current loop in a uniform field shown in Fig. 26.23*a*. Current flowing along the top and bottom of the loop results in upward and downward forces of equal magnitude, and neither a net force nor a net torque is associated with these forces. Currents flowing along the vertical sides also result in equal but opposite forces. However, as Fig. 26.23*b* shows, these forces result in a net torque about a vertical axis through the center of the loop. The vertical sides have length a and the currents are perpendicular to the horizontal magnetic field, so the force on each has magnitude $F_{side} = IaB$. The vertical sides are half the loop width b from the axis, so the torque due to each is $\tau_{side} = \frac{1}{2}bF_{side}\sin\theta = \frac{1}{2}bIaB\sin\theta$. Torques on the two sides are in the same direction (out of the page in Fig. 26.23*b*), so the net torque is $\tau = IabB\sin\theta = IAB\sin\theta$, with A the loop area. We've already identified IA as the magnitude of the loop's magnetic dipole moment $\vec{\mu}$ and, given the direction of $\vec{\mu}$ as shown in Figs. 26.21 and 26.23*b*, we can incorporate the directionality and the factor $\sin\theta$ into a cross product:

$$\vec{\tau} = \vec{\mu} \times \vec{B} \qquad \text{(torque on a magnetic dipole)} \tag{26.15}$$

analogous to the torque on an electric dipole.

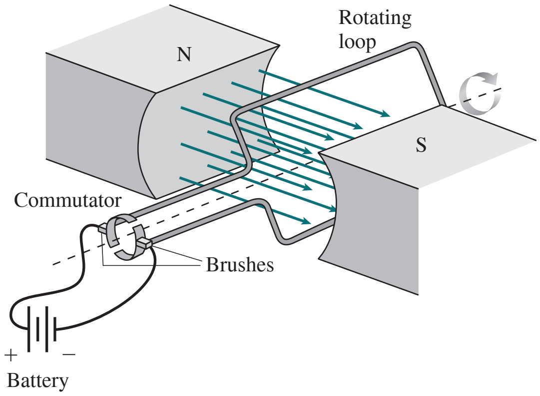
The magnetic torque of Equation 26.15 causes magnetic dipoles—current loops—to align with their dipole moment vectors along the magnetic field. It takes work to rotate a dipole out of alignment with the field, and in analogy with Equation 20.11 the associated potential energy is

$$U = -\vec{\mu} \cdot \vec{B} \tag{26.16}$$

In a nonuniform field, a dipole also experiences a net force. That's why the nonuniform field near the poles of a bar magnet attracts magnetic materials that, as we'll see in the next section, contain magnetic dipoles.

The torque on a magnetic dipole is important in many technologies, including electric motors and MRI imaging. Some satellites use the torque produced by Earth's magnetic field to orient themselves in space; with electricity generated from solar panels powering current loops, there's no fuel to run out.

APPLICATION **Electric Motors**



Electric motors are so much a part of our lives that we hardly think of them. Yet refrigerators, disk drives, subway trains, vacuum cleaners, power tools, food processors, fans, washing machines, water pumps, hybrid cars, and most industrial machinery would be impossible without electric motors.

At the heart of every electric motor is a current loop in a magnetic field. But instead of a steady current, the loop carries a current that reverses to keep the loop always spinning. In direct-current (DC) motors, this is achieved through the electrical contacts that provide current to the loop. The figure shows how current flows to the loop through a pair of stationary *brushes* that contact rotating conductors called the *commutator*. The current loop rotates to align with the field, but just as it does so, the brushes cross the gaps in the commutator and reverse the loop's current and therefore its dipole moment vector. Now the loop swings another 180° to its new "desired" position, but again the commutator reverses the current and so the loop rotates continuously. A rigid shaft spinning with the coils delivers mechanical energy. Thus the motor is a device that converts electrical energy to mechanical energy. The magnetic field is an intermediary in this energy conversion.

EXAMPLE 26.5 **Torque on a Current Loop: Designing an Electric Car Motor**

Nissan's Leaf electric car uses a 110-kW electric motor that develops a maximum torque of 320 N·m. Suppose you want to produce this torque in a motor like the one in the preceding Application, consisting of a 700-turn rectangular coil measuring 30 cm by 20 cm in a uniform field of 25 mT. How much current does the motor need?

INTERPRET This problem is about an electric motor, which according to the Application is essentially a current loop in a magnetic field. We're given the torque and asked for the current.

DEVELOP Equation 26.15, $\vec{\tau} = \vec{\mu} \times \vec{B}$, determines the torque on a current loop. Figure 26.24 is a sketch of the loop at the point of maximum torque, $\tau_{max} = \mu B$, which occurs when $\sin\theta = 1$. To solve for the current, we need the magnetic dipole moment from Equation 26.13, $\mu = NIA$. Then $\tau_{max} = NIAB$.

EVALUATE Solving for I using the maximum torque and the loop dimensions gives

$$I = \frac{\tau_{max}}{NAB} = \frac{320\ \text{N}\cdot\text{m}}{(700)(0.30\ \text{m})(0.20\ \text{m})(0.025\ \text{T})} = 300\ \text{A}$$

ASSESS That's a large current, but propelling a car is a big job. The actual Leaf motor operates at about 400 V, so its 110-kW power requires current $I = P/V = 280$ A, close to our answer. However, the Leaf's motor uses a much more complex design than the motor in this example or in the preceding Application.

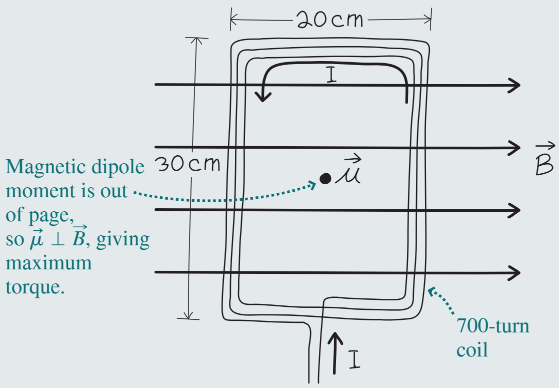


FIGURE 26.24 Loop for the motor of Example 26.5, shown in the position of maximum torque.

26.7 Magnetic Matter

LO 26.7 *Qualitatively describe ferromagnetism, paramagnetism, and diamagnetism.*

So far, we've said remarkably little about magnets. That's because magnetism is fundamentally about moving electric charge. Magnets and magnetic matter are just a minor manifestation of this universal phenomenon.

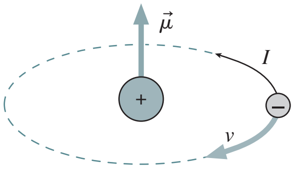


FIGURE 26.25 In the classical model of the atom, the circling electron constitutes a miniature current loop. The current is opposite the motion because the electron is negative. Drawing is only suggestive; the electron's intrinsic magnetic dipole moment is usually more important than that resulting from its orbital motion.

The magnetism of everyday magnets and of magnetic materials like iron results from atomic-scale current loops. An electron orbiting a nucleus constitutes a simple current loop and therefore has a magnetic dipole moment (Fig. 26.25). More importantly, an electron possesses an intrinsic magnetic dipole moment associated with a quantum-mechanical angular momentum called spin. Interactions among these magnetic moments determine the magnetic properties of atoms and of bulk matter. The details necessarily involve quantum mechanics; here we give a qualitative overview of magnetism in matter, which manifests itself in three distinct forms.

Ferromagnetism

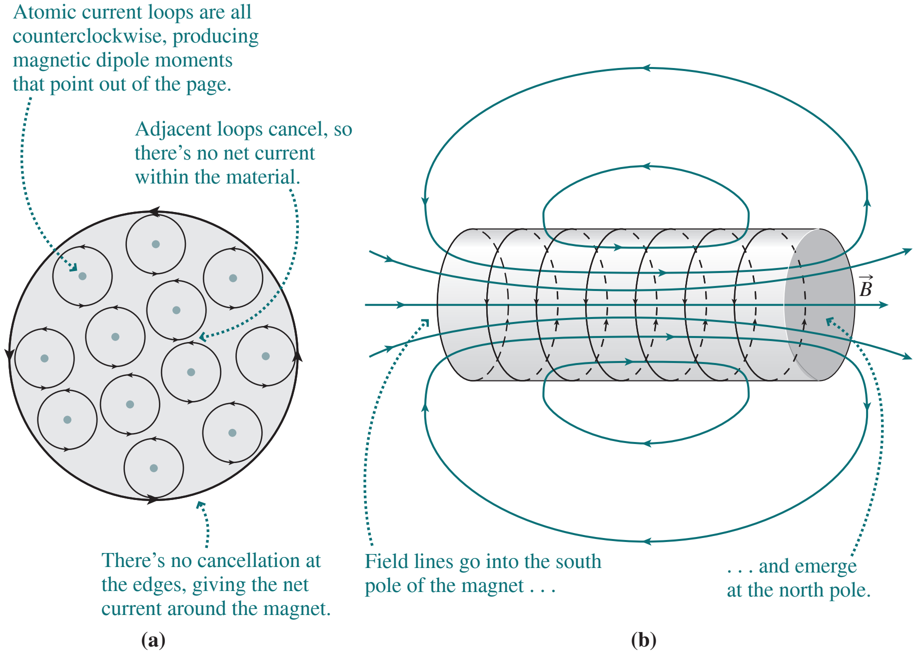
The magnetism you're familiar with is **ferromagnetism**, which is limited to a few substances, including iron, nickel, cobalt, and some alloys and compounds. Strong interactions among atomic magnetic moments result in **magnetic domains**, regions that contain 10^{17}–10^{21} atoms whose magnetic moments are all aligned in the same direction. Normally the magnetic moments of different domains point in random directions, so there's no net magnetic moment. But when an external magnetic field is applied, the domains all align and the material acquires a net magnetic moment. If the field is nonuniform, the material then experiences a net force, which is why ferromagnetic materials are attracted to magnets.

So-called **hard** ferromagnetic materials retain their magnetism even after the applied field is removed; the result is a permanent magnet. A bar magnet, for example, has its internal magnetic moments aligned along its long dimension. You can think of its field as arising from currents circulating around the surface of the magnet (Fig. 26.26)—currents that ultimately result from the superposition of individual atomic current loops. Computer disks and credit card strips use hard ferromagnetic materials that retain information as patterns of permanent magnetization. **Soft** ferromagnetic materials, in contrast, don't hold magnetization. They're used where magnetization must be turned on and off rapidly, as in the "heads" that write information to computer disks. Ferromagnetism disappears at the so-called **Curie temperature**, as random thermal motions disrupt the organized alignment of magnetic dipoles; for iron this phase transition occurs at 1043 K.

Paramagnetism

Many substances that aren't ferromagnetic nevertheless consist of atoms or molecules that have permanent magnetic dipole moments. There's no strong interaction among the individual dipoles, so these **paramagnetic** materials respond only weakly to external magnetic fields. Paramagnetic effects are generally significant only at very low temperatures.

FIGURE 26.26 (a) Cross section of a bar magnet, showing atomic current loops all aligned the same way and making a net current around the magnet. (b) Side view showing the field that results from this magnetization current.



Diamagnetism

Materials without intrinsic magnetic moments can have moments induced by changes in an applied magnetic field. Whereas ferromagnetic and paramagnetic materials are attracted to magnets, these **diamagnetic** materials are repelled. We'll explore the origins of diamagnetism in Chapter 27.

Magnetic Permeability and Susceptibility

We found in Chapter 20 that the alignment of molecular electric dipoles reduces the electric field in a material. In paramagnetic and ferromagnetic materials, alignment of magnetic dipoles causes an *increase* in the field. Figure 26.27 shows that this difference occurs because the magnetic field within a current loop points in the *same* direction as the loop's magnetic dipole moment, whereas the internal field of an electric dipole is *opposite* the dipole moment. Ferromagnetic behavior is further complicated because it depends on the material's past history, which is what makes permanent magnets possible. Coils for electromagnets and computer disk "heads" are wound on ferromagnetic cores to provide a much stronger magnetic field than the coil current alone could produce.

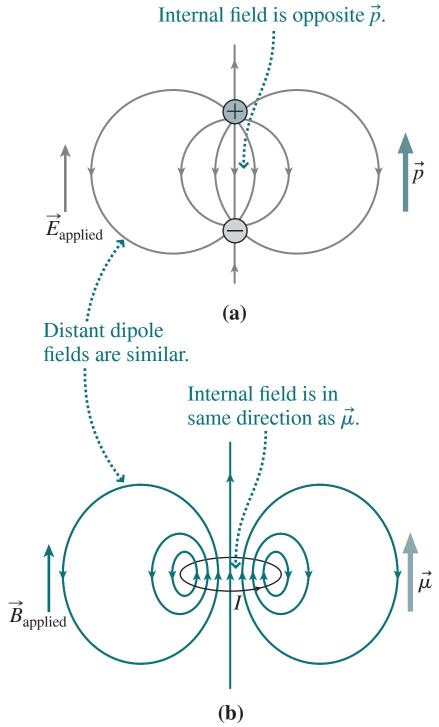


FIGURE 26.27 Internal fields of electric and magnetic dipoles have opposite directions. (a) Electric dipoles reduce an applied electric field; (b) magnetic dipoles increase an applied magnetic field.

GOT IT?

26.7 Which of the following best describes the phenomenon responsible for ordinary magnets? (a) high concentrations of magnetic monopoles; (b) collective alignment of atomic magnetic dipoles; (c) electric currents due to free charges circulating in magnetic materials; (d) separation of positive and negative electric charges to the magnetic poles

26.8 Ampère's Law

LO 26.8 *Describe Ampère's law and use it to evaluate magnetic fields with sufficient symmetry.*

Computing electric fields with Coulomb's law in Chapter 20 was cumbersome for all but the simplest charge distributions. In Chapter 21 we saw how Gauss's law greatly simplified electric-field calculations for symmetric charge distributions. Is there an analogous approach for magnetic fields? Gauss's law for magnetism, Equation 26.14, won't do because it doesn't relate a magnetic field to its source—namely, moving charge.

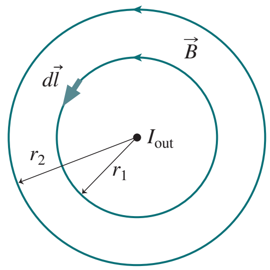


FIGURE 26.28 Two magnetic field lines surrounding a wire carrying current out of the page.

Figure 26.28 shows two of the circular magnetic field lines surrounding a long wire carrying a current I out of the page. Imagine moving around the inner circle, and as you go a little way, take the product of a small length dl of the circular path with the magnetic field in the direction you're going. Here you're moving in the direction of the field, so that product is $B\,dl$; more generally, it's the dot product $\vec{B}\cdot d\vec{l}$. Now add up all these products around the circle. Formally, the result is the line integral $\oint \vec{B}\cdot d\vec{l}$, where the circle indicates that we're integrating around a closed path. In this case the integral becomes just $\oint B\,dl$ because $\vec{B}$ and $d\vec{l}$ are in the same direction. But here the field magnitude is given by Equation 26.10: $B = \mu_0 I/2\pi r$, where we've replaced y with the radius r. Since r has the constant value r_1 on the inner circle in Fig. 26.28, the integral becomes $(\mu_0 I/2\pi r_1)\oint dl$. Now $\oint dl$ is the total length of the circular path, or its circumference $2\pi r_1$. So the value of $\oint \vec{B}\cdot d\vec{l}$ is $\mu_0 I$. If you try the same thing for the outer circle in Fig. 26.28, r_2 replaces r_1, but the result is the same: $\oint \vec{B}\cdot d\vec{l} = \mu_0 I$, independent of the radius.

We get the same result even if the path doesn't coincide with a field line, as Fig. 26.29 suggests. On the radial segments of the path shown, $\vec{B}\cdot d\vec{l} = 0$ and there's no contribution to the integral. On segment AB, the field is stronger than if we had stayed on CD, but the segment is proportionately shorter and the integral remains unchanged. We could approximate any arbitrary path as a sequence of radial segments and circular arcs, showing that the value of $\oint \vec{B}\cdot d\vec{l}$ is independent of path as long as the path surrounds the current I. The value of that integral is simply $\mu_0 I$. Magnetic fields obey the superposition principle, so this result

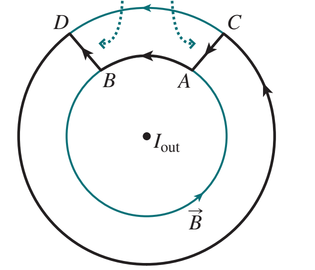


FIGURE 26.29 A closed loop that does not coincide with a field line. The line integral $\oint \vec{B}\cdot d\vec{l}$ around this loop has the same value $\mu_0 I$ that it has around a circular loop.