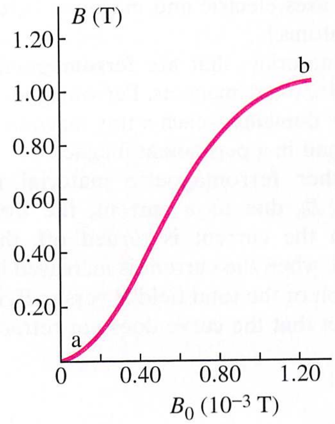

FIGURE 20–43 Total magnetic field B in an iron-core toroid as a function of the external field B_0 (B_0 is caused by the current I in the coil).

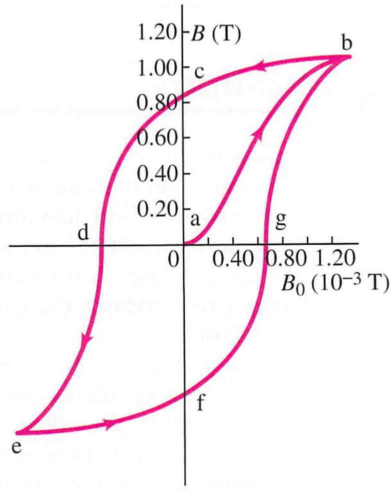

FIGURE 20–44 Hysteresis curve.

Fig. 20–43. (Note the different scales: $B \gg B_0$.) At the initial point a, the domains are randomly oriented. As B_0 increases, the domains become more and more aligned until at point b, nearly all are aligned. The iron is said to be approaching **saturation**. Next, suppose current in the coils is reduced, so the field B_0 decreases. If the current (and B_0) is reduced to zero, point c in Fig. 20–44, the domains do *not* become completely random. Instead, some permanent magnetism remains in the iron core. If the current is increased in the opposite direction, enough domains can be turned around so the total B becomes zero at point d. As the reverse current is increased further, the iron approaches saturation in the opposite direction, point e. Finally, if the current is again reduced to zero and then increased in the original direction, the total field follows the path efgb, again approaching saturation at point b.

Notice that the field did not pass through the origin (point a) in this cycle. The fact that the curve does not retrace itself on the same path is called **hysteresis**. The curve bcdefgb is called a **hysteresis loop**. In such a cycle, much energy is transformed to thermal energy (friction) due to realigning of the domains. Note that at points c and f, the iron core is magnetized even though there is no current in the coils. These points correspond to a permanent magnet.

Hysteresis

Summary

A magnet has two **poles**, north and south. The north pole is that end which points toward geographic north when the magnet is freely suspended. Like poles of two magnets repel each other, whereas unlike poles attract.

We can imagine that a **magnetic field** surrounds every magnet. The SI unit for magnetic field is the **tesla** (T).

Electric currents produce magnetic fields. For example, the lines of magnetic field due to a current in a straight wire form circles around the wire, and the field exerts a force on magnets (or currents) near it.

A magnetic field exerts a force on an electric current. For a straight wire of length l carrying a current I, the force has magnitude

$$F = IlB \sin\theta, \qquad \textbf{(20–1)}$$

where θ is the angle between the magnetic field $\vec{\mathbf{B}}$ and the current. The direction of the force is perpendicular to the current-carrying wire and to the magnetic field, and is given by a right-hand rule. Equation 20–1 serves as the definition of magnetic field $\vec{\mathbf{B}}$.

Similarly, a magnetic field exerts a force on a charge q moving with velocity v of magnitude

$$F = qvB \sin\theta, \qquad \textbf{(20–3)}$$

where θ is the angle between $\vec{\mathbf{v}}$ and $\vec{\mathbf{B}}$. The direction of $\vec{\mathbf{F}}$ is perpendicular to $\vec{\mathbf{v}}$ and to $\vec{\mathbf{B}}$ (again a right-hand rule). The path of a charged particle moving perpendicular to a uniform magnetic field is a circle.

The magnitude of the magnetic field produced by a current I in a long straight wire, at a distance r from the wire, is

$$B = \frac{\mu_0}{2\pi}\frac{I}{r}. \qquad \textbf{(20–6)}$$

Two currents exert a force on each other via the magnetic field each produces. Parallel currents in the same direction attract each other; currents in opposite directions repel.

The magnetic field inside a long tightly wound solenoid is

$$B = \mu_0 NI/l, \qquad \textbf{(20–8)}$$

where N is the number of loops in a length l of coil, and I is the current in each loop.

[*$\textbf{Ampère's law}$ states that around any chosen closed loop path, the sum of each path segment Δl times the component of $\vec{\mathbf{B}}$ parallel to the segment equals μ_0 times the current I enclosed by the closed path:

$$\Sigma B_{\parallel} \Delta l = \mu_0 I_{\text{encl}}. \tag{20–9}$$]

[*The torque τ on N loops of current I in a magnetic field $\vec{\mathbf{B}}$ is

$$\tau = NIAB \sin\theta. \tag{20–10}$$

The force or torque exerted on a current-carrying wire by a magnetic field is the basis for operation of many devices, such as meters, motors, and loudspeakers.]

[*A **mass spectrometer** uses electric and magnetic fields to determine the masses of atoms.]

Iron and a few other materials that are **ferromagnetic** can be made into strong permanent magnets. Ferromagnetic materials are made up of tiny **domains**—each a tiny magnet—which are preferentially aligned in a permanent magnet.

[*When iron or another ferromagnetic material is placed in a magnetic field B_0 due to a current, the iron becomes magnetized. When the current is turned off, the material remains magnetized; when the current is increased in the opposite direction, a graph of the total field B versus B_0 is a **hysteresis loop**, and the fact that the curve does not retrace itself is called **hysteresis**.]

Questions

1. A compass needle is not always balanced parallel to the Earth's surface, but one end may dip downward. Explain.

2. Draw the magnetic field lines around a straight section of wire carrying a current horizontally to the left.

3. In what direction are the magnetic field lines surrounding a straight wire carrying a current that is moving directly away from you?

4. A horseshoe magnet is held vertically with the north pole on the left and south pole on the right. A wire passing between the poles, equidistant from them, carries a current directly away from you. In what direction is the force on the wire?

5. Will a magnet attract any metallic object, or only those made of iron? (Try it and see.) Why is this so?

6. Two iron bars attract each other no matter which ends are placed close together. Are both magnets? Explain.

7. The magnetic field due to current in wires in your home can affect a compass. Discuss the effect in terms of currents, including if they are ac or dc.

8. If a negatively charged particle enters a region of uniform magnetic field which is perpendicular to the particle's velocity, will the kinetic energy of the particle increase, decrease, or stay the same? Explain your answer. (Neglect gravity and assume there is no electric field.)

9. In Fig. 20–45, charged particles move in the vicinity of a current-carrying wire. For each charged particle, the arrow indicates the direction of motion of the particle, and the + or − indicates the sign of the charge. For each of the particles, indicate the direction of the magnetic force due to the magnetic field produced by the wire.

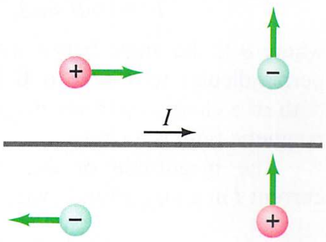

FIGURE 20–45 Question 9.

10. Three particles, a, b, and c, enter a magnetic field as shown in Fig. 20–46. What can you say about the charge on each particle?

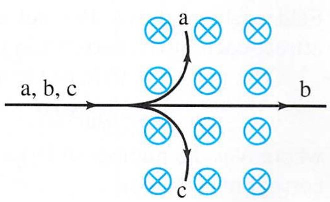

FIGURE 20–46 Question 10.

11. A positively charged particle in a nonuniform magnetic field follows the trajectory shown in Fig. 20–47. Indicate the direction of the magnetic field everywhere in space, assuming the path is always in the plane of the page, and indicate the relative magnitudes of the field in each region.

FIGURE 20–47 Question 11.

12. Can an iron rod attract a magnet? Can a magnet attract an iron rod? What must you consider to answer these questions?

13. Explain why a strong magnet held near a CRT television screen (Section 17–10) causes the picture to become distorted. Also, explain why the picture sometimes goes completely black where the field is the strongest. [But don't risk damage to your TV by trying this.]

14. Suppose you have three iron rods, two of which are magnetized but the third is not. How would you determine which two are the magnets without using any additional objects?

15. Can you set a resting electron into motion with a magnetic field? With an electric field? Explain.

16. A charged particle is moving in a circle under the influence of a uniform magnetic field. If an electric field that points in the same direction as the magnetic field is turned on, describe the path the charged particle will take.

17. The force on a particle in a magnetic field is the idea behind *electromagnetic pumping*. It is used to pump metallic fluids (such as sodium) and to pump blood in artificial heart machines. The basic design is shown in Fig. 20–48. An electric field is applied perpendicular to a blood vessel and to a magnetic field. Explain how ions are caused to move. Do positive and negative ions feel a force in the same direction?

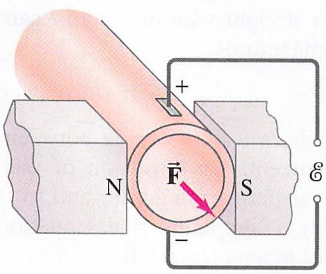

FIGURE 20–48 Electromagnetic pumping in a blood vessel. Question 17.

18. A beam of electrons is directed toward a horizontal wire carrying a current from left to right (Fig. 20–49). In what direction is the beam deflected?

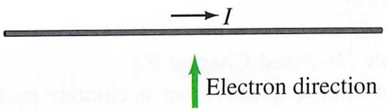

FIGURE 20–49 Question 18.

19. Describe electric and/or magnetic fields that surround a moving electric charge.

20. A charged particle moves in a straight line through a particular region of space. Could there be a nonzero magnetic field in this region? If so, give two possible situations.

21. If a moving charged particle is deflected sideways in some region of space, can we conclude, for certain, that $\vec{\mathbf{B}} \neq 0$ in that region? Explain.

22. In a particular region of space there is a uniform magnetic field $\vec{\mathbf{B}}$. Outside this region, $B = 0$. Can you inject an electron from outside into the field perpendicularly so that it will move in a closed circular path in the field? What if the electron is injected near the center?

23. How could you tell whether moving electrons in a certain region of space are being deflected by an electric field or by a magnetic field (or by both)?

24. How can you make a compass without using iron or other ferromagnetic material?

25. Two long wires carrying equal currents I are at right angles to each other, but don't quite touch. Describe the magnetic force one exerts on the other.

26. A horizontal current-carrying wire, free to move in Earth's gravitational field, is suspended directly above a second, parallel, current-carrying wire. (*a*) In what direction is the current in the lower wire? (*b*) Can the upper wire be held in stable equilibrium due to the magnetic force of the lower wire? Explain.

27. Why will either pole of a magnet attract an unmagnetized piece of iron?

28. An unmagnetized nail will not attract an unmagnetized paper clip. However, if one end of the nail is in contact with a magnet, the other end *will* attract a paper clip. Explain.

* **29.** Two ions have the same mass, but one is singly ionized and the other is doubly ionized. How will their positions on the film of a mass spectrometer (Fig. 20–39) differ?

30. What would be the effect on B inside a long solenoid if (*a*) the diameter of all the loops was doubled, (*b*) the spacing between loops was doubled, or (*c*) the solenoid's length was doubled along with a doubling in the total number of loops?

31. A type of magnetic switch similar to a solenoid is a **relay** (Fig. 20–50). A relay is an electromagnet (the iron rod inside the coil does not move) which, when activated, attracts a piece of iron on a pivot. Design a relay to close an electrical switch. A relay is used when you need to switch on a circuit carrying a very large current but you do not want that large current flowing through the main switch. For example, the starter switch of a car is connected to a relay so that the large current needed for the starter doesn't pass to the dashboard switch.

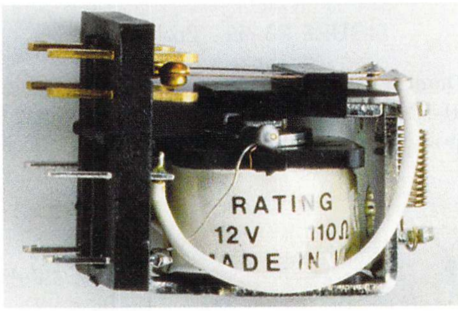

FIGURE 20–50 Question 31.

Problems

20–3 Force on Electric Current in Magnetic Field

1. (I) (*a*) What is the magnitude of the force per meter of length on a straight wire carrying an 8.40-A current when perpendicular to a 0.90-T uniform magnetic field? (*b*) What if the angle between the wire and field is 45.0°?

2. (I) Calculate the magnitude of the magnetic force on a 160-m length of straight wire stretched between two towers carrying a 150-A current. The Earth's magnetic field of 5.0×10^{-5} T makes an angle of 65° with the wire.

3. (I) How much current is flowing in a wire 4.80 m long if the maximum force on it is 0.750 N when placed in a uniform 0.0800-T field?

4. (II) A 1.5-m length of wire carrying 4.5 A of current is oriented horizontally. At that point on the Earth's surface, the dip angle of the Earth's magnetic field makes an angle of 38° to the wire. Estimate the magnitude of the magnetic force on the wire due to the Earth's magnetic field of 5.5×10^{-5} T at this point.

5. (II) The force on a wire carrying 8.75 A is a maximum of 1.28 N when placed between the pole faces of a magnet. If the pole faces are 55.5 cm in diameter, what is the approximate strength of the magnetic field?

6. (II) The magnetic force per meter on a wire is measured to be only 35% of its maximum possible value. Sketch the relationship of the wire and the field if the force had been a maximum, and sketch the relationship as it actually is, calculating the angle between the wire and the magnetic field.

7. (II) The force on a wire is a maximum of 6.50×10^{-2} N when placed between the pole faces of a magnet. The current flows horizontally to the right and the magnetic field is vertical. The wire is observed to "jump" toward the observer when the current is turned on. (*a*) What type of magnetic pole is the top pole face? (*b*) If the pole faces have a diameter of 10.0 cm, estimate the current in the wire if the field is 0.16 T. (*c*) If the wire is tipped so that it makes an angle of 10.0° with the horizontal, what force will it now feel?

8. (II) Suppose a straight 1.00-mm-diameter copper wire could just "float" horizontally in air because of the force due to the Earth's magnetic field $\vec{\mathbf{B}}$, which is horizontal, perpendicular to the wire, and of magnitude 5.0×10^{-5} T. What current would the wire carry? Does the answer seem feasible? Explain briefly.

20–4 Force on Charge Moving in Magnetic Field

9. (I) Alpha particles of charge $q = +2e$ and mass $m = 6.6 \times 10^{-27}$ kg are emitted from a radioactive source at a speed of 1.6×10^7 m/s. What magnetic field strength would be required to bend them into a circular path of radius $r = 0.25$ m?

10. (I) Determine the magnitude and direction of the force on an electron traveling 8.75×10^5 m/s horizontally to the east in a vertically upward magnetic field of strength 0.75 T.

11. (I) Find the direction of the force on a negative charge for each diagram shown in Fig. 20–51, where $\vec{\mathbf{v}}$ (green) is the velocity of the charge and $\vec{\mathbf{B}}$ (blue) is the direction of the magnetic field. (⊗ means the vector points inward. ⊙ means it points outward, toward you.)

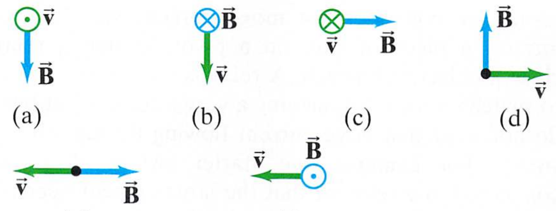

FIGURE 20–51 Problem 11.

12. (I) Determine the direction of $\vec{\mathbf{B}}$ for each case in Fig. 20–52, where $\vec{\mathbf{F}}$ represents the maximum magnetic force on a positively charged particle moving with velocity $\vec{\mathbf{v}}$.

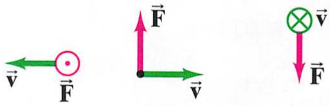

FIGURE 20–52 Problem 12.

13. (I) An electron is projected vertically upward with a speed of 1.70×10^6 m/s into a uniform magnetic field of 0.350 T that is directed horizontally away from the observer. Describe the electron's path in this field.

14. (II) A 5.0-MeV (kinetic energy) proton enters a 0.20-T field, in a plane perpendicular to the field. What is the radius of its path?

15. (II) An electron experiences the greatest force as it travels 2.9×10^6 m/s in a magnetic field when it is moving northward. The force is upward and of magnitude 7.2×10^{-13} N. What are the magnitude and direction of the magnetic field?

16. (II) What is the velocity of a beam of electrons that go undeflected when passing through perpendicular electric and magnetic fields of magnitude 8.8×10^3 V/m and 3.5×10^{-3} T, respectively? What is the radius of the electron orbit if the electric field is turned off?

17. (II) A doubly charged helium atom whose mass is 6.6×10^{-27} kg is accelerated by a voltage of 2100 V. (*a*) What will be its radius of curvature if it moves in a plane perpendicular to a uniform 0.340-T field? (*b*) What is its period of revolution?

18. (II) A proton (mass m_p), a deuteron $(m = 2m_p,\ Q = e)$, and an alpha particle $(m = 4m_p,\ Q = 2e)$ are accelerated by the same potential difference V and then enter a uniform magnetic field $\vec{\mathbf{B}}$, where they move in circular paths perpendicular to $\vec{\mathbf{B}}$. Determine the radius of the paths for the deuteron and alpha particle in terms of that for the proton.

19. (II) Show that the time T required for a particle of charge q moving with constant speed v to make one circular revolution in a uniform magnetic field $\vec{\mathbf{B}}$ ($\perp \vec{\mathbf{v}}$) is

$$T = \frac{2\pi m}{qB}.$$

[*Hint:* see Example 20–5 and Chapter 5.]

20. (II) A particle of charge q moves in a circular path of radius r in a uniform magnetic field B. Show that its momentum is $p = qBr$.

21. (II) A particle of mass m and charge q moves in a circular path in a magnetic field B. Show that its kinetic energy is proportional to r^2, the square of the radius of curvature of its path.

22. (II) Show that the angular momentum of the particle in Problem 21 is $L = qBr^2$ about the center of the circle.

23. (III) A 3.40-g bullet moves with a speed of 160 m/s perpendicular to the Earth's magnetic field of 5.00×10^{-5} T. If the bullet possesses a net charge of 13.5×10^{-9} C, by what distance will it be deflected from its path due to the Earth's magnetic field after it has traveled 1.00 km?

24. (III) Suppose the Earth's magnetic field at the equator has magnitude 0.40×10^{-4} T and a northerly direction at all points. Estimate the speed a singly ionized uranium ion ($m = 238$ u, $q = e$) would need to circle the Earth 5.0 km above the equator. Can you ignore gravity?

25. (III) A proton moving with speed $v = 2.0 \times 10^5$ m/s in a field-free region abruptly enters an essentially uniform magnetic field $B = 0.850$ T ($\vec{\mathbf{B}} \perp \vec{\mathbf{v}}$). If the proton enters the magnetic field region at a 45° angle as shown in Fig. 20–53, (*a*) at what angle does it leave, and (*b*) at what distance x does it exit the field?

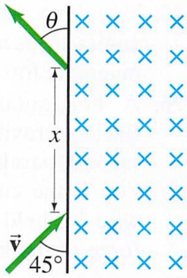

FIGURE 20–53 Problem 25.

20–5 and 20–6 Magnetic Field of Straight Wire, Force Between Two Wires

26. (I) A jumper cable used to start a stalled vehicle carries a 65-A current. How strong is the magnetic field 6.0 cm away from it? Compare to the Earth's magnetic field.

27. (I) If an electric wire is allowed to produce a magnetic field no larger than that of the Earth $(0.55 \times 10^{-4}\,\text{T})$ at a distance of 25 cm, what is the maximum current the wire can carry?

28. (I) In Fig. 20–54, a long straight wire carries current I out of the page toward you. Indicate, with appropriate arrows, the direction of $\vec{\mathbf{B}}$ at each of the points C, D, and E in the plane of the page.

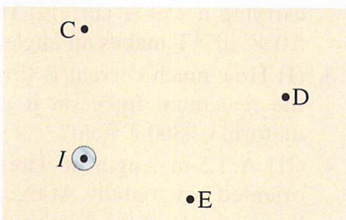

FIGURE 20–54 Problem 28.

29. (I) A vertical straight wire carrying an upward 24-A current exerts an attractive force per unit length of 8.8×10^{-4} N/m on a second parallel wire 7.0 cm away. What current (magnitude and direction) flows in the second wire?

30. (I) Determine the magnitude and direction of the force between two parallel wires 35 m long and 6.0 cm apart, each carrying 25 A in the same direction.

31. (II) An experiment on the Earth's magnetic field is being carried out 1.00 m from an electric cable. What is the maximum allowable current in the cable if the experiment is to be accurate to $\pm 1.0\%$?

32. (II) A power line carries a current of 95 A along the tops of 8.5-m-high poles. What is the magnitude of the magnetic field produced by this wire at the ground? How does this compare with the Earth's field of about $\frac{1}{2}$ G?

33. (II) Two long thin parallel wires 13.0 cm apart carry 25-A currents in the same direction. Determine the magnetic field at point P, 12.0 cm from one wire and 5.0 cm from the other (Fig. 20–55).

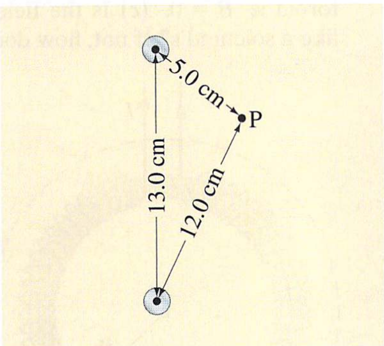

FIGURE 20–55 Problem 33.

34. (II) A horizontal compass is placed 18 cm due south from a straight vertical wire carrying a 35-A current downward. In what direction does the compass needle point at this location? Assume the horizontal component of the Earth's field at this point is 0.45×10^{-4} T and the magnetic declination is 0°.

35. (II) A long horizontal wire carries 22.0 A of current due north. What is the net magnetic field 20.0 cm due west of the wire if the Earth's field there points north but downward, 37° below the horizontal, and has magnitude 5.0×10^{-5} T?

36. (II) A straight stream of protons passes a given point in space at a rate of 1.5×10^9 protons/s. What magnetic field do they produce 2.0 m from the beam?

37. (II) Determine the magnetic field midway between two long straight wires 2.0 cm apart in terms of the current I in one when the other carries 15 A. Assume these currents are (*a*) in the same direction, and (*b*) in opposite directions.

38. (II) A long pair of wires conducts 25.0 A of dc current to, and from, an instrument. If the insulated wires are of negligible diameter but are 2.8 mm apart, what is the magnetic field 10.00 cm from their midpoint, in their plane (Fig. 20–56)? Compare to the magnetic field of the Earth.

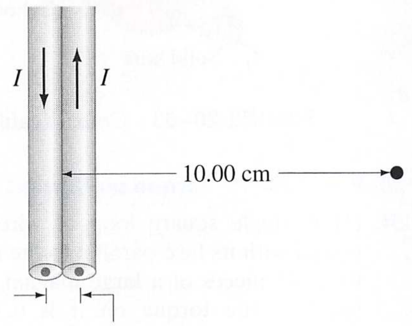

FIGURE 20–56 Problems 38 and 39.

39. (II) A third wire is placed in the plane of the two wires shown in Fig. 20–56, parallel and just to the right. If it carries 25.0 A upward, what force per meter of length does it exert on each of the other two wires? Assume it is 2.8 mm from the nearest wire, center to center.

40. (II) A compass needle points 23° E of N outdoors. However, when it is placed 12.0 cm to the east of a vertical wire inside a building, it points 55° E of N. What are the magnitude and direction of the current in the wire? The Earth's field there is 0.50×10^{-4} T and is horizontal.

41. (II) A rectangular loop of wire lies in the same plane as a straight wire, as shown in Fig. 20–57. There is a current of 2.5 A in both wires. Determine the magnitude and direction of the net force on the loop.

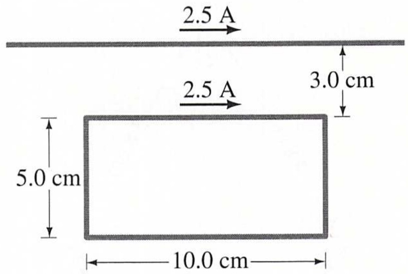

FIGURE 20–57 Problem 41.

42. (II) A long horizontal wire carries a current of 48 A. A second wire, made of 2.5-mm-diameter copper wire and parallel to the first, is kept in suspension magnetically 15 cm below (Fig. 20–58). (*a*) Determine the magnitude and direction of the current in the lower wire. (*b*) Is the lower wire in stable equilibrium? (*c*) Repeat parts (*a*) and (*b*) if the second wire is suspended 15 cm *above* the first due to the latter's field.

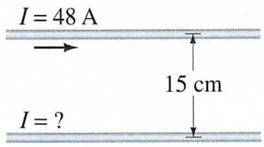

FIGURE 20–58 Problem 42.

43. (II) Two long wires are oriented so that they are perpendicular to each other. At their closest, they are 20.0 cm apart (Fig. 20–59). What is the magnitude of the magnetic field at a point midway between them if the top one carries a current of 20.0 A and the bottom one carries 5.0 A?

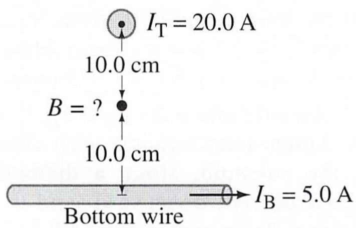

FIGURE 20–59 Problem 43.

44. (II) Two long straight parallel wires are 15 cm apart. Wire A carries 2.0 A current. Wire B's current is 4.0 A in the same direction. (*a*) Determine the magnetic field magnitude due to wire A at the position of wire B. (*b*) Determine the magnetic field due to wire B at the position of wire A. (*c*) Are these two magnetic fields equal and opposite? Why or why not? (*d*) Determine the force on wire A due to wire B, and the force on wire B due to wire A. Are these two forces equal and opposite? Why or why not?

45. (II) Three long parallel wires are 3.8 cm from one another. (Looking along them, they are at three corners of an equilateral triangle.) The current in each wire is 8.00 A, but its direction in wire M is opposite to that in wires N and P (Fig. 20–60). Determine the magnetic force per unit length on each wire due to the other two.

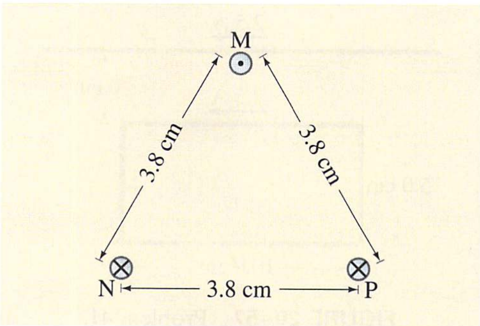

FIGURE 20–60 Problems 45, 46, and 74.

46. (II) In Fig. 20–60, determine the magnitude and direction of the magnetic field at the midpoint of the side of the triangle between wire M and wire N.

47. (II) Let two long parallel wires, a distance d apart, carry equal currents I in the same direction. One wire is at $x = 0$, the other is at $x = d$, Fig. 20–61. Determine $\vec{\mathbf{B}}$ along the x axis between the wires as a function of x.

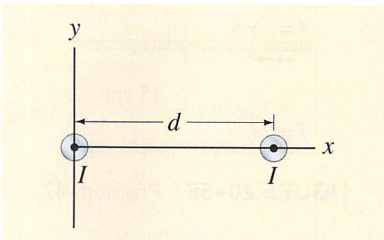

FIGURE 20–61 Problem 47.

20–7 Solenoids and Electromagnets

48. (I) A thin 12-cm-long solenoid has a total of 420 turns of wire and carries a current of 2.0 A. Calculate the field inside near the center.

49. (I) A 30.0-cm long solenoid 1.25 cm in diameter is to produce a field of 0.385 T at its center. How much current should the solenoid carry if it has 975 turns of the wire?

50. (II) A 550-turn solenoid is 15 cm long. The current in it is 33 A. A 3.0-cm-long straight wire cuts through the center of the solenoid, along a diameter. This wire carries a 22-A current downward (and is connected by other wires that don't concern us). What is the force on this wire assuming the solenoid's field points due east?

51. (III) You have 1.0 kg of copper and want to make a practical solenoid that produces the greatest possible magnetic field for a given voltage. Should you make your copper wire long and thin, short and fat, or something else? Consider other variables, such as solenoid diameter, length, and so on.

* 20–8 Ampère's Law

* 52. (II) A toroid is a solenoid in the shape of a circle (Fig. 20–62). Use Ampère's law along the circular path, shown dashed in Fig. 20–62a, to determine that the magnetic field (*a*) inside the toroid is $B = \mu_0 NI/2\pi R$, where N is the total number of turns, and (*b*) outside the toroid is $B = 0$. (*c*) Is the field inside a toroid uniform like a solenoid's? If not, how does it vary?

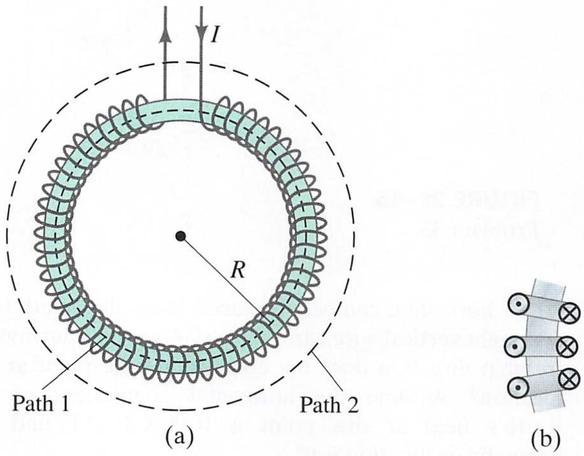

FIGURE 20–62 Problem 52. (a) A toroid. (b) A section of the toroid showing direction of the current for three loops: ⊙ means current toward you, and ⊗ means current away from you.

* 53. (III) (*a*) Use Ampère's law to show that the magnetic field between the conductors of a *coaxial cable* (Fig. 20–63) is $B = \mu_0 I/2\pi r$ if r is greater than the radius of the inner wire and less than the radius of the outer cylindrical braid. (*b*) Show that $B = 0$ outside the coaxial cable.

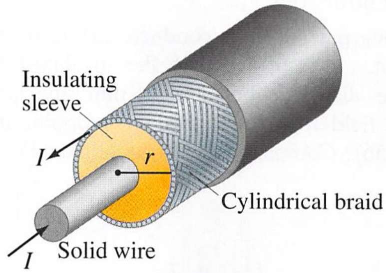

FIGURE 20–63 Coaxial cable. Problem 53.

* 20–9 and 20–10 Torque on Current Loop, Applications

* 54. (I) A single square loop of wire 22.0 cm on a side is placed with its face parallel to the magnetic field between the pole pieces of a large magnet. When 6.30 A flows in the coil, the torque on it is 0.325 m·N. What is the magnetic field strength?

* 55. (I) A galvanometer needle deflects full scale for a 53.0-μA current. What current will give full-scale deflection if the magnetic field weakens to 0.860 of its original value?

* 56. (I) If the restoring spring of a galvanometer weakens by 25% over the years, what current will give full-scale deflection if it originally required 36 μA?

* 57. (I) If the current to a motor drops by 12%, by what factor does the output torque change?

* 58. (II) Show that the magnetic dipole moment M of an electron orbiting the proton nucleus of a hydrogen atom is related to the orbital angular momentum L of the electron by

$$M = \frac{e}{2m} L.$$

* 59. (II) A circular coil 16.0 cm in diameter and containing nine loops lies flat on the ground. The Earth's magnetic field at this location has magnitude 5.50×10^{-5} T and points into the Earth at an angle of 56.0° below a line pointing due north. If a 7.20-A clockwise current passes through the coil, (*a*) determine the torque on the coil, and (*b*) which edge of the coil rises up: north, east, south, or west?

* 20–11 Mass Spectrometer

* 60. (I) Protons move in a circle of radius 5.10 cm in a 0.566-T magnetic field. What value of electric field could make their paths straight? In what direction must it point?

* 61. (I) In a mass spectrometer, germanium atoms have radii of curvature equal to 21.0, 21.6, 21.9, 22.2, and 22.8 cm. The largest radius corresponds to an atomic mass of 76 u. What are the atomic masses of the other isotopes?

* 62. (II) Suppose the electric field between the electric plates in the mass spectrometer of Fig. 20–39 is 2.48×10^4 V/m and the magnetic fields $B = B' = 0.68$ T. The source contains carbon isotopes of mass numbers 12, 13, and 14 from a long-dead piece of a tree. (To estimate atomic masses, multiply by 1.67×10^{-27} kg.) How far apart are the lines formed by the singly charged ions of each type on the photographic film? What if the ions were doubly charged?

* 63. (II) A mass spectrometer is being used to monitor air pollutants. It is difficult, however, to separate molecules with nearly equal mass such as CO (28.0106 u) and N_2 (28.0134 u). How large a radius of curvature must a spectrometer have if these two molecules are to be separated on the film by 0.50 mm?

* 64. (II) One form of mass spectrometer accelerates ions by a voltage V before they enter a magnetic field B. The ions are assumed to start from rest. Show that the mass of an ion is $m = qB^2R^2/2V$, where R is the radius of the ions' path in the magnetic field and q is their charge.

20–12 Ferromagnetism, Hysteresis

* 65. (I) A long thin solenoid has 430 loops of wire per meter, and a 25-A current flows through the wire. If the permeability of the iron is $3000\mu_0$, what is the total field B inside the solenoid?

* 66. (II) An iron-core solenoid is 38 cm long and 1.8 cm in diameter, and has 640 turns of wire. The magnetic field inside the solenoid is 2.2 T when 48 A flows in the wire. What is the permeability μ at this high field strength?

General Problems

67. Protons with momentum 4.8×10^{-16} kg·m/s are magnetically steered clockwise in a circular path 2.0 km in diameter at Fermi National Accelerator Laboratory in Illinois. Determine the magnitude and direction of the field in the magnets surrounding the beam pipe.

68. A proton and an electron have the same kinetic energy upon entering a region of constant magnetic field. What is the ratio of the radii of their circular paths?

69. The power cable for an electric trolley (Fig. 20–64) carries a horizontal current of 330 A toward the east. The Earth's magnetic field has a strength 5.0×10^{-5} T and makes an angle of dip of 22° at this location. Calculate the magnitude and direction of the magnetic force on a 15-m length of this cable.

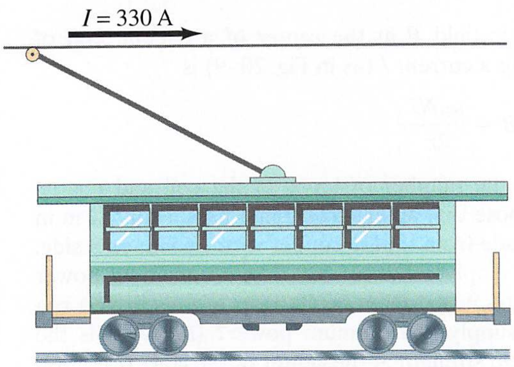

FIGURE 20–64 Problem 69.

70. Calculate the force on an airplane which has acquired a net charge of 1550 μC and moves with a speed of 120 m/s perpendicular to the Earth's magnetic field of 5.0×10^{-5} T.

71. Near the equator, the Earth's magnetic field points almost horizontally to the north and has magnitude $B = 0.50 \times 10^{-4}$ T. What should be the magnitude and direction for the velocity of an electron if its weight is to be exactly balanced by the magnetic force?

72. A doubly charged helium atom, whose mass is 6.6×10^{-27} kg, is accelerated by a voltage of 2400 V. (*a*) What will be its radius of curvature in a uniform 0.240-T field? (*b*) What is its period of revolution?

73. A sort of "projectile launcher" is shown in Fig. 20–65. A large current moves in a closed loop composed of fixed rails, a power supply, and a very light, almost frictionless bar touching the rails. A magnetic field is perpendicular to the plane of the circuit. If the bar has a length $L = 22$ cm, a mass of 1.5 g, and is placed in a field of 1.7 T, what constant current flow is needed to accelerate the bar from rest to 28 m/s in a distance of 1.0 m? In what direction must the magnetic field point?

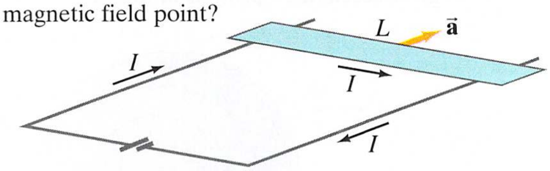

FIGURE 20–65 Problem 73.

74. In Fig. 20–60 the top wire is 1.00-mm-diameter copper wire and is suspended in air due to the two magnetic forces from the bottom two wires. The current flow through the two bottom wires is 95 A in each. Calculate the required current flow in the suspended wire.

75. Two stiff parallel wires a distance l apart in a horizontal plane act as rails to support a light metal rod of mass m (perpendicular to each rail), Fig. 20–66. A magnetic field $\vec{\mathbf{B}}$, directed vertically upward (outward in the diagram), acts throughout. At $t = 0$, wires connected to the rails are connected to a constant current source and a current I begins to flow through the system. Determine the speed of the rod, which starts from rest at $t = 0$, as a function of time (a) assuming no friction between the rod and the rails, and (b) if the coefficient of friction is μ_k. (c) Does the rod move east or west if the current through it heads north?

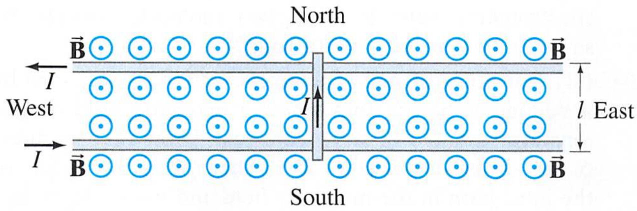

FIGURE 20–66 Looking down on a rod sliding on rails. Problem 75.

76. Estimate the approximate maximum deflection of the electron beam near the center of a TV screen due to the Earth's 5.0×10^{-5} T field. Assume the CRT screen (Section 17–10) is 22 cm from the electron gun, where the electrons are accelerated (a) by 2.0 kV, or (b) by 30 kV. Note that in color TV sets, the CRT beam must be directed accurately to within less than 1 mm in order to strike the correct phosphor. Because the Earth's field is significant here, mu-metal shields are used to reduce the Earth's field in the CRT.

77. The **cyclotron** (Fig. 20–67) is a device used to accelerate elementary particles such as protons to high speeds. Particles starting at point A with some initial velocity travel in circular orbits in the magnetic field B. The particles are accelerated to higher speeds each time they pass through the gap between the metal "dees," where there is an electric field E. (There is no electric field inside the hollow metal dees.) The electric field changes direction each half-cycle, owing to an ac voltage $V = V_0 \sin 2\pi f t$, so that the particles are increased in speed at each passage through the gap. (a) Show that the frequency f of the voltage must be $f = Bq/2\pi m$, where q is the charge on the particles and m their mass. (b) Show that the kinetic energy of the particles increases by $2qV_0$ each revolution, assuming that the gap is small. (c) If the radius of the cyclotron is 2.0 m and the magnetic field strength is 0.50 T, what will be the maximum kinetic energy of accelerated protons in MeV?

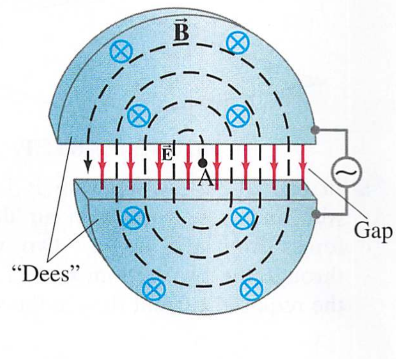

FIGURE 20–67 A cyclotron. Problem 77.

78. Four very long straight parallel wires, located at the corners of a square of side l, carry equal currents I_0 perpendicular to the page as shown in Fig. 20–68. Determine the magnitude and direction of $\vec{\mathbf{B}}$ at the center C of the square.

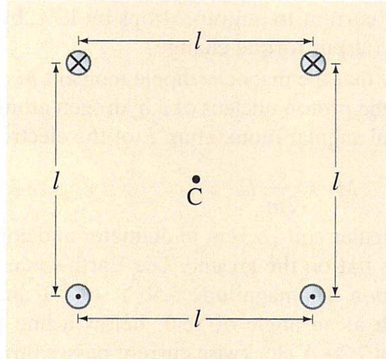

FIGURE 20–68 Problem 78.

79. Magnetic fields are very useful in particle accelerators for "beam steering"; that is, the magnetic fields can be used to change the beam's direction without altering its speed (Fig. 20–69). Show how this works with a beam of protons. What happens to protons that are not moving with the speed that the magnetic field is designed for? If the field extends over a region 5.0 cm wide and has a magnitude of 0.33 T, by approximately what angle will a beam of protons traveling at 1.0×10^7 m/s be bent?

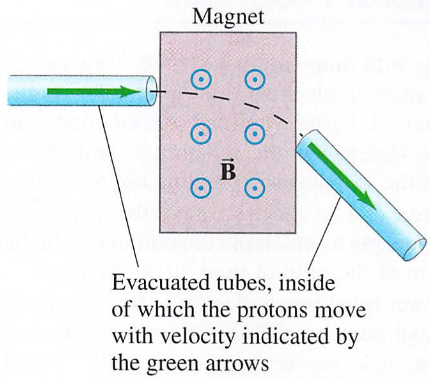

FIGURE 20–69 Problem 79.

80. The magnetic field B at the center of a circular coil of wire carrying a current I (as in Fig. 20–9) is

$$B = \frac{\mu_0 NI}{2r},$$

where N is the number of loops in the coil and r is its radius. Suppose that an electromagnet uses a coil 1.2 m in diameter made from square copper wire 1.6 mm on a side. The power supply produces 120 V at a maximum power output of 4.0 kW. (a) How many turns are needed to run the power supply at maximum power? (b) What is the magnetic field strength at the center of the coil? (c) If you use a greater number of turns and this same power supply (so the voltage remains at 120 V), will a greater magnetic field strength result? Explain.

81. Near the Earth's poles the magnetic field is about 1 G (1×10^{-4} T). Imagine a simple model in which the Earth's field is produced by a single current loop around the equator. Roughly estimate the current this loop would carry. [*Hint:* use the formula given in Problem 80.]

82. You want to get an idea of the magnitude of magnetic fields produced by overhead power lines. You estimate that the two wires are each about 30 m above the ground and are about 3 m apart. The local power company tells you that the lines operate at 10 kV and provide a maximum of 40 MW to the local area. Estimate the maximum magnetic field you might experience walking under these power lines, and compare to the Earth's field. [For an ac current, values are rms, and the magnetic field will be changing.]

83. (*a*) What value of magnetic field would make a beam of electrons, traveling to the right at a speed of 4.8×10^6 m/s, go undeflected through a region where there is a uniform electric field of 10,000 V/m pointing vertically up? (*b*) What is the direction of the magnetic field if it is known to be perpendicular to the electric field? (*c*) What is the frequency of the circular orbit of the electrons if the electric field is turned off?

84. A proton follows a spiral path through a gas in a magnetic field of 0.010 T, perpendicular to the plane of the spiral, as shown in Fig. 20–70. In two successive loops, at points P and Q, the radii are 10.0 mm and 8.5 mm, respectively. Calculate the change in the kinetic energy of the proton as it travels from P to Q.

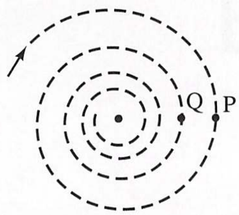

FIGURE 20–70 Problem 84.

85. A 32-cm-long solenoid, 1.8 cm in diameter, is to produce a 0.30-T magnetic field at its center. If the maximum current is 5.7 A, how many turns must the solenoid have?

86. Two long straight aluminum wires, each of diameter 0.50 mm, carry the same current but in opposite directions. They are suspended by 0.50-m-long strings as shown in Fig. 20–71. If the suspension strings make an angle of 3.0° with the vertical, what is the current in the wires?

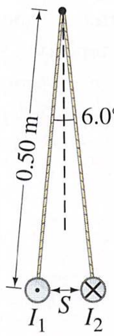

FIGURE 20–71 Problem 86.

87. An electron enters a uniform magnetic field $B = 0.23$ T at a 45° angle to $\vec{\mathbf{B}}$. Determine the radius r and pitch p (distance between loops) of the electron's helical path assuming its speed is 3.0×10^6 m/s. See Fig. 20–72.

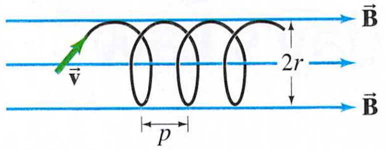

FIGURE 20–72 Problem 87.

Answers to Exercises

A: Near the poles, where the field lines are closer together.
B: Counterclockwise.
C: 0.15 N.
D: Zero.
E: Negative; the direction of the helical path would be reversed.
F: 2.0 cm.