Q17 "When you connect a metal wire between two oppositely charged metal blocks, electrons on the negatively charged block jump to the positively charged block." Explain briefly what is wrong with this statement.

Q18 What would happen if an electron with energy less than the ionization energy of a nitrogen molecule collided with a nitrogen molecule?

Q19 At high altitudes the air is less dense. If the density of air were half that at sea level, how would d, the mean free path of an electron in air, change? (1) d would be the same. (2) d would be twice as long. (3) d would be half as long. (4) d would be 1/4 as long. (5) d would be 4 times as long.

Q20 If the radius of an air molecule were twice as large, how would d, the mean free path of an electron in air, change? (1) d would be the same. (2) d would be twice as long. (3) d would be half as long. (4) d would be 1/4 as long. (5) d would be 4 times as long.

Q21 If you observed that under certain conditions an electric field six times as great as usual were required to ionize air, what might you conclude about the mean free path under these conditions? Give your answer as a ratio of the mean free path under these conditions to the mean free path at STP.

Q22 Metal sphere 1 is charged negatively, and metal sphere 2 is not charged in Figure 20.93.

Figure 20.93

(a) Using the conventions for diagrams described and used in this textbook, show the charge distribution for both spheres. **(b)** The spheres are moved closer to each other (using insulating supports so as not to change their charge). When they are a certain short distance apart, a spark is seen for a brief instant. Explain qualitatively what determines this distance for the spark to be produced. (Why doesn't the spark occur when the spheres are farther apart? What's special about this distance?) **(c)** After the spark stops, show the charge distribution for both spheres, and explain briefly but completely how this new charge distribution came about.

Q23 In very dry weather, if you shuffle across the carpet wearing rubber-soled shoes and then bring your finger near a metal object such as a doorknob, you will probably get a shock and see a spark. How this can occur is puzzling, since rubber is an insulator, so charge can't move through the soles of your shoes. Explain this process in detail, with appropriate diagrams. Make sure that you answer the following questions: **(a)** Carry out an experiment to determine the sign of the charge on the sole of your shoe after rubbing it on carpet, wool, or other cloth. Explain the test you did. (If you are unable to obtain results, choose a sign to use in the rest of the discussion.) **(b)** Draw a diagram that includes both the shoe and the rest of your body. Include all relevant charges and fields. **(c)** Suppose that a spark occurred when your finger was 1 cm from the doorknob. Draw two diagrams showing your hand, the doorknob, all relevant charges, and all contributions to the electric field at relevant locations: when your finger is 1.5 cm from the doorknob (no spark yet), and when your finger is 1 cm from the doorknob (spark starts). On the basis of these diagrams, explain why the spark starts only when your finger is close enough (1 cm) to the doorknob and not farther away. **(d)** At what location do you think the spark starts, and why (why not somewhere else)? **(e)** Why does the spark stop?

PROBLEMS

Section 20.1

•**P24** An electron is moving in the y direction at a speed $v = 2\times10^7$ m/s at a point where there is a magnetic field $B = 3.5$ T in the z direction (Figure 20.94). What are the magnitude and direction of the magnetic force on the moving electron? Draw the force vector on a diagram of the situation.

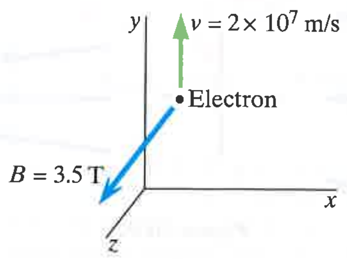

Figure 20.94

•**P25** At a particular instant a proton is traveling in the $-x$ direction, with speed 5×10^5 m/s. At the location of the proton there is a magnetic field of magnitude 0.24 T in the $-y$ direction, due to current running in a nearby coil. What are the direction and magnitude of the magnetic force on the proton?

•**P26** At a particular instant an electron is traveling in the $-x$ direction, with speed 4×10^5 m/s. At the location of the electron there is a magnetic field of magnitude 0.27 T in the $+z$ direction, due to a large bar magnet. What are the direction and magnitude of the magnetic force on the electron?

•**P27** At a particular instant an electron is traveling in the $+z$ direction, with speed 8×10^5 m/s. At the location of the electron there is a magnetic field of magnitude 0.32 T in the $-z$ direction, due to a large bar magnet. What are the direction and magnitude of the magnetic force on the electron?

•**P28** To become familiar with the order of magnitude of magnetic effects, consider the situation in a television cathode ray tube (not a flat-panel TV). In order to bend the electron trajectory so that the electron hits the top of the screen rather than going straight through to the center of the screen, you need a radius of curvature in the magnetic field of about 20 cm (Figure 20.95). If the electrons are accelerated through a 15,000 V potential difference, they have a speed of 0.7×10^8 m/s. Calculate the magnitude of the magnetic field required to make the electrons hit the top of the screen. Is the magnetic field into or out of the page?

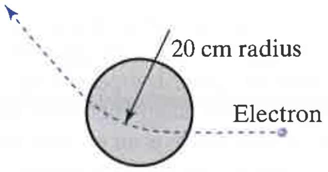

Figure 20.95

•P29 An alpha particle (consisting of two protons and two neutrons) is moving at constant speed in a circle, perpendicular to a uniform magnetic field applied by some current-carrying coils, making one clockwise revolution every 80 ns (Figure 20.96). If the speed is small compared to the speed of light, what is the numerical magnitude B of the magnetic field made by the coils? What is the direction of this magnetic field?

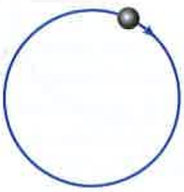

Figure 20.96

••P30 An electron and a proton are both in motion near each other as shown in Figure 20.97; at this instant they are a distance r apart. The proton is moving with speed v_p at an angle θ to the horizontal, and the electron is moving straight up with speed v_e.

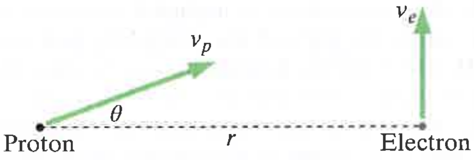

Figure 20.97

(a) Calculate the x and y components of the force that the proton exerts on the electron. First calculate the electric field and magnetic field that the proton produces at the location of the electron, then calculate the forces that these fields exert on the electron. **(b)** Calculate the x and y components of the force that the electron exerts on the proton. First calculate the electric field and magnetic field that the electron produces at the location of the proton, then calculate the forces that these fields exert on the proton. (In a completely correct quantitative calculation we would have to use the relativistically correct fields.) **(c)** Consider carefully your results. Are the magnetic forces on electron and proton equal and opposite? Does reciprocity hold for magnetic forces? **(d)** Will the total momentum of the two particles remain constant? Is this a violation of conservation of momentum for an isolated system?

See the comments at the end of Question Q3.

••P31 A mass spectrometer is a tool used to determine accurately the mass of individual ionized atoms or molecules, or to separate atoms or molecules that have similar but slightly different masses. For example, you can deduce the age of a small sample of cloth from an ancient tomb by using a mass spectrometer to determine the relative abundances of carbon-14 (whose nucleus contains 6 protons and 8 neutrons) and carbon-12 (the most common isotope, whose nucleus contains 6 protons and 6 neutrons).

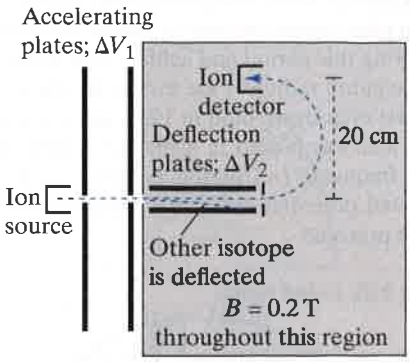

Figure 20.98

A particular kind of mass spectrometer is shown in Figure 20.98. Carbon from the sample is ionized in the ion source at the left. The resulting singly ionized ${}^{12}C^+$ and ${}^{14}C^+$ ions have negligibly small initial velocities (and can be considered to be at rest). They are accelerated through the potential difference ΔV_1. They then enter a region where the magnetic field has a fixed magnitude $B = 0.2$ T. The ions pass through electric deflection plates that are 1 cm apart and have a potential difference ΔV_2 that is adjusted so that the electric deflection and the magnetic deflection cancel each other for a particular isotope: one isotope goes straight through, and the other isotope is deflected and misses the entrance to the next section of the spectrometer. The distance from the entrance to the fixed ion detector is a distance of 20 cm.

There are controls that let you vary the accelerating potential ΔV_1 and the deflection potential ΔV_2 in order that only ${}^{12}C^+$ or ${}^{14}C^+$ ions go all the way through the system and reach the detector. You count each kind of ion for fixed times and thus determine the relative abundances. The various deflections ensure that you count only the desired type of ion for a particular setting of the two voltages.

Carry out the following calculations, and give brief explanations of your work: **(a)** Determine which accelerating plate is positive (left or right), which deflection plate is positive (upper or lower), and the direction of the magnetic field. **(b)** Determine the appropriate numerical values of ΔV_1 and ΔV_2 for ${}^{12}C$. Carry out your intermediate calculations algebraically, so that you can use the algebraic results in part (c). **(c)** Determine the appropriate numerical values of ΔV_1 and ΔV_2 for ${}^{14}C$.

Background: In organic material the ratio of ${}^{14}C$ to ${}^{12}C$ depends on how old the material is, which is the basis for carbon-14 dating. ${}^{14}C$ is continually produced in the upper atmosphere by nuclear reactions caused by cosmic rays (high-energy charged particles from outer space, mainly protons), and ${}^{14}C$ is radioactive with a half-life of 5700 y. When a cotton plant is growing, some of the CO_2 it extracts from the air to build tissue contains ${}^{14}C$ that has diffused down from the upper atmosphere. After the cotton has been harvested, however, there is no further intake of ${}^{14}C$ from the air, and the cosmic rays that create ${}^{14}C$ in the upper atmosphere can't penetrate the atmosphere and reach the cloth. Thus the amount of ${}^{14}C$ in cotton cloth continually decreases with time, while the amount of nonradioactive ${}^{12}C$ remains constant.

••P32 The design and operation of a cyclotron (Figure 20.99) was discussed in Section 20.1. **(a)** Show that the period of the motion, the time between one kick to the right and the next kick in the same direction, does not depend on the current speed of the proton at speeds small compared to the speed of light. As a result, we can place across the dees a simple sinusoidal potential difference having this period and achieve continual acceleration out to the maximum radius of the cyclotron. **(b)** One of Ernest Lawrence's first cyclotrons, built in 1932, had a diameter of only about 30 cm and was placed in a magnetic field of about 1 T. What was the frequency (= 1/period, in hertz = cycles per second) of the sinusoidal potential difference placed across the dees to accelerate the protons?

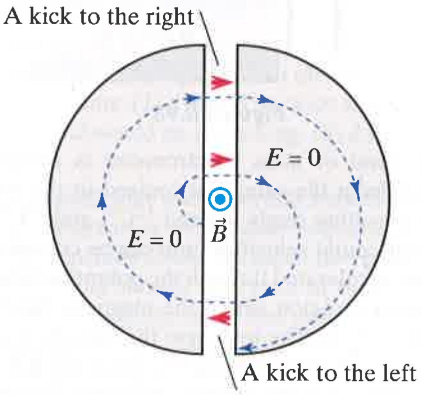

Figure 20.99

(c) Show that the equivalent accelerating potential of this little cyclotron was about a million volts! That is, the kinetic energy gain from the center to the outermost radius was $\Delta K = e\Delta V_{\text{eq}}$, with $\Delta V_{\text{eq}} = 1 \times 10^6$ V. (*Hint:* Calculate the final speed at the outermost radius.) **(d)** If the sinusoidal potential difference applied to the dees had an amplitude of 500 V (that is, it varied between +500 and −500 V), show that it took about 65 μs for a proton to move from the center to the outer radius.

••P33 The thin circular coil in Figure 20.100 has radius $r = 15$ cm and contains $N = 3$ turns of Nichrome wire. The coil has a resistance of 6 Ω. A small compass is placed at the center of the coil. With the battery disconnected, the compass needle points to the right, in the plane of the coil. The apparatus is located near the equator, where the Earth's magnetic field B_{Earth} is horizontal, with a magnitude of about 4×10^{-5} T.

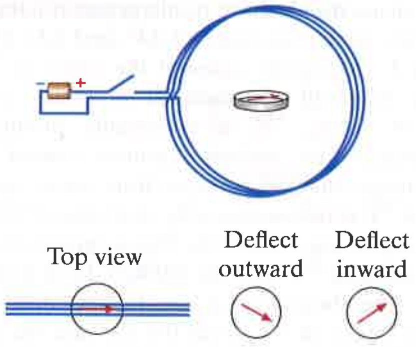

Figure 20.100

(a) When the 1.5 V battery is connected, predict the deflection of the compass needle. If you have to make any approximations, state what they are. Is the deflection outward or inward as seen from above? What is the magnitude of the deflection? **(b)** The compass is removed. The current in the coil continues to run. An electron is at the center of the coil and is moving with speed $v = 5 \times 10^6$ m/s into the page (perpendicular to the plane of the coil). In addition to the magnetic fields in the region due to the Earth and the coil, there is an electric field at the center of the coil (due to charges not shown in Figure 20.100), and this electric field points upward and has a magnitude $E = 250$ V/m. What are the magnitude and direction of the force on the electron at this moment? (You can neglect the gravitational force, which easily can be shown to be negligible.)

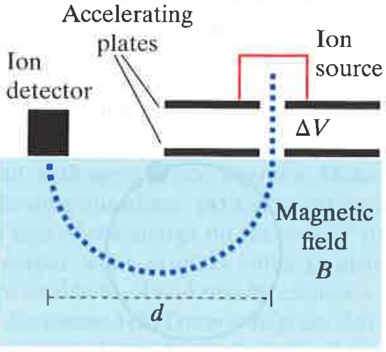

Figure 20.101

••P34 In the simple mass spectrometer shown in Figure 20.101, positive ions are generated in the ion source. They are released, traveling at very low speed, into the region between two accelerating plates between which there is a potential difference ΔV. In the shaded region there is a uniform magnetic field $\vec{B}$; outside this region there is negligible magnetic field. The semicircle traces the path of one singly charged positive ion of mass M, which travels through the accelerating plates into the magnetic field region, and hits the ion detector as shown. Determine the appropriate magnitude and direction of the magnetic field $\vec{B}$, in terms of the known quantities shown in Figure 20.101. Explain all steps in your reasoning.

••P35 A long solenoid with diameter 4 cm is in a vacuum, and a lithium nucleus (4 neutrons and 3 protons) is in a clockwise circular orbit inside the solenoid (Figure 20.102). It takes 50 ns (50×10^{-9} s) for the lithium nucleus to complete one orbit.

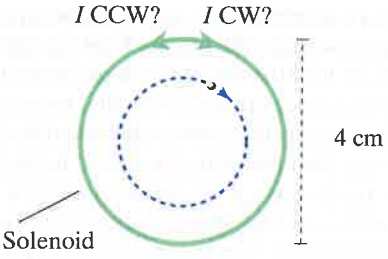

Figure 20.102

(a) Does the current in the solenoid run clockwise or counterclockwise? Explain, including physics diagrams. **(b)** What is the magnitude of the magnetic field made by the solenoid?

••P36 A long straight wire suspended in the air carries a conventional current of 8.2 A in the $-x$ direction as shown in Figure 20.103 (the wire runs along the x axis). At a particular instant an electron at location $\langle 0, -0.003, 0 \rangle$ m has velocity $\langle -1.5 \times 10^5, -1.8 \times 10^5, 0 \rangle$ m/s.

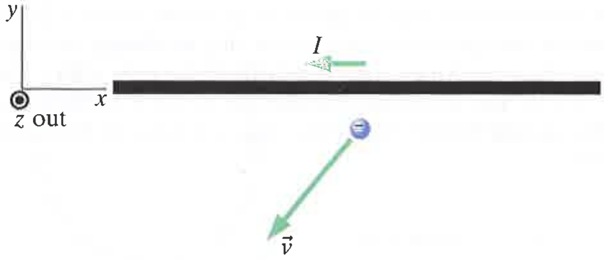

Figure 20.103

(a) What is the (vector) magnetic field due to the wire at the location of the electron? **(b)** What is the (vector) magnetic force on the electron due to the current in the wire? **(c)** If the moving particle were a proton instead of an electron, what would be the (vector) magnetic force on the proton?

Section 20.2

•**P37** A wire is oriented along the x axis. It is connected to two batteries, and a conventional current of 1.8 A runs through the wire in the $+x$ direction. Along 0.25 m of the length of the wire there is a magnetic field of 0.54 T in the $+y$ direction, due to a large magnet nearby. At other locations in the circuit, the magnetic field due to external sources is negligible. What are the direction and magnitude of the magnetic force on the wire?

•**P38** A 1.5 V battery is connected to a resistive wire whose resistance is 5 Ω. The wire is laid out in the form of a rectangle 50 cm by 3 cm (Figure 20.104). What are the approximate magnitude and direction of the magnetic force that the upper part of the wire exerts on the lower part of the wire in the diagram? Explain briefly.

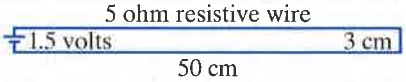

Figure 20.104

•**P39** A current-carrying wire is oriented along the y axis. It passes through a region 0.6 m long in which there is a magnetic field of 4.5 T in the $+z$ direction. The wire experiences a force of 14.9 N in the $-x$ direction. **(a)** What is the magnitude of the conventional current in the wire? **(b)** What is the direction of the conventional current in the wire?

•**P40** If your flashlight battery has an internal resistance of about 1/4 Ω, and your bar magnet produces a magnetic field of about 0.1 T near one end of the magnet, what is the approximate magnitude of the magnetic force on 5 cm of a wire that short-circuits the battery (Figure 20.105)? Indicate the direction of this force on a diagram. Check your direction experimentally.

Figure 20.105

••**P41** A Nichrome wire has the shape of two quarter-circles of radius a and b, connected by straight sections as shown in Figure 20.106. The wire carries conventional current I in the direction shown.

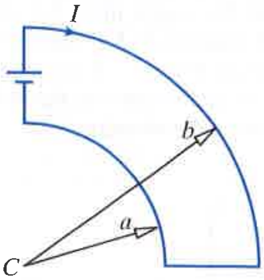

Figure 20.106

(a) Calculate the direction and magnitude of the magnetic field at point C, the center of the quarter-circles. Briefly explain your work, including a diagram. **(b)** At a particular instant, an electron is at point C, traveling to the right with speed v. Calculate the direction and magnitude of the magnetic force on the electron. Briefly explain your work, including a diagram.

••**P42** A long wire carries a current I_1 upward, and a rectangular loop of height h and width w carries a current I_2 clockwise (Figure 20.107). The loop is a distance d away from the long wire. The long wire and the rectangular loop are in the same plane. Find the magnitude and direction of the net magnetic force exerted by the long wire on the rectangular loop. Briefly explain your work, including a diagram.

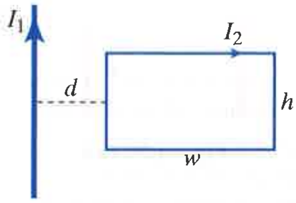

Figure 20.107

••**P43** A metal rod of length $L = 12$ cm and mass $m = 70$ g has metal loops at both ends, which go around two metal poles (Figure 20.108). The rod is in good electrical contact with the poles but can slide freely up and down. The metal poles are connected by wires to a battery, and a current of $I = 5$ A flows through the rod. A magnet supplies a large uniform magnetic field B in the region of the rod, large enough that you can neglect the magnetic fields due to the 5 A current. The magnetic field is oriented so as to have the maximum effect on the rod. The rod sits at rest a distance $d = 4$ cm above the table. What are the magnitude and direction of the magnetic field in the region of the rod? Briefly explain your work, including a diagram.

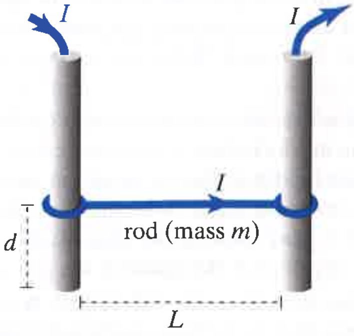

Figure 20.108

Section 20.3

•P44 An object of charge q is moving in the x direction with speed v. Throughout the region there is a uniform electric field in the y direction of magnitude E (Figure 20.109). Determine a direction and magnitude B for a uniform magnetic field such that the net electric and magnetic force on the moving charge is zero. Draw $\vec{B}$ on a diagram of the situation.

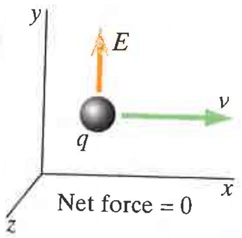

Figure 20.109

•P45 In Figure 20.110 a particle with a charge of +9 nC travels to the left in a straight line at constant speed through a region where the electric field is 3800 V/m in the $-y$ direction and the magnetic field is 0.4 T in the $+z$ direction. What is the speed of the particle?

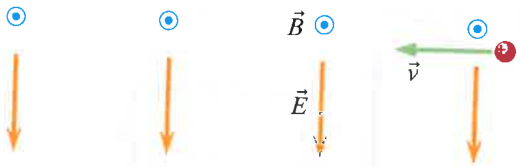

Figure 20.110

•P46 An electron travels with velocity $\langle 5\times10^5, 0, 0\rangle$ m/s. It enters a region in which there is a uniform magnetic field of $\langle 0, 0.9, 0\rangle$ T. **(a)** What is the (vector) magnetic force on the electron? **(b)** Despite the magnetic force, the electron continues to travel in a straight line at constant speed. You conclude that there must be another force acting on the electron. Since you know there is also an electric field in this region, you decide that the other force must be an electric force. What is this (vector) electric force? **(c)** What is the (vector) electric field in this region that is responsible for the electric force?

•P47 A proton traveling with speed 3105 m/s in the $+x$ direction passes through a region in which there is a uniform magnetic field of magnitude 0.6 T in the $+y$ direction. You want to keep the proton traveling in a straight line at constant speed. To do this, you can turn on an apparatus that can create a uniform electric field throughout the region. What (vector) electric field should you apply?

•P48 A proton moves at constant velocity in the $+y$ direction, through a region in which there is an electric field and a magnetic field. The electric field is in the $+x$ direction and has magnitude 200 V/m. The magnetic field is in the $-z$ direction and has magnitude 0.95 T. **(a)** What is the magnitude of the net force on the proton? **(b)** What is the speed of the proton?

••P49 Two long straight wires carrying 8 A of conventional current are connected by a three-quarter-circular arc of radius 0.035 m (Figure 20.111). (The rest of the circuit is far enough away that it contributes little magnetic field in this region.) Electric fields are also present in this region, due to charges not shown on the drawing. An electron is moving to the right with a speed of 5.7×10^5 m/s as it passes through the center C of the arc, and at that instant the net electric and magnetic force on the electron is zero.

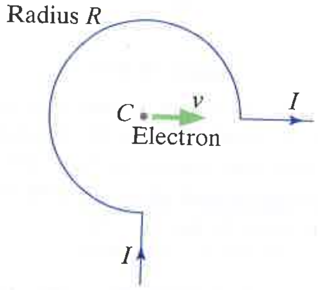

Figure 20.111

(a) What is the direction of the magnetic field at the center C due to the current? **(b)** What is the direction of the electric field at the center C? **(c)** What is the magnitude of the magnetic field at the center C due to the current? **(d)** What is the magnitude of the electric field at the center C?

••P50 An electron travels with velocity $\langle 0, 0, -2.9\times10^6\rangle$ m/s in a region between a pair of very large charged plates, separated by a distance of 4.5 mm. In this region there is also a uniform magnetic field. The velocity of the electron remains constant throughout this region. The magnetic field, due to large coils outside the region, is measured and is found to be $\langle 0, -0.27, 0\rangle$ T.

On paper, draw a diagram showing the electron's velocity, the direction of the magnetic field in the region, the direction of the magnetic force on the electron, the direction of the electric force on the electron, and the direction of the electric field in the region. Use your diagram to answer the following questions. **(a)** What is the direction of the magnetic force on the electron? **(b)** What is the direction of the electric force on the electron? **(c)** What is the direction of the electric field in the region? **(d)** What is the magnitude of the magnetic force on the electron? **(e)** What is the absolute value of the potential difference between the plates?

••P51 A cathode ray tube (CRT), as shown in Figures 20.112 and 20.113, is an evacuated glass tube. A current runs through a filament at the right end of the tube.

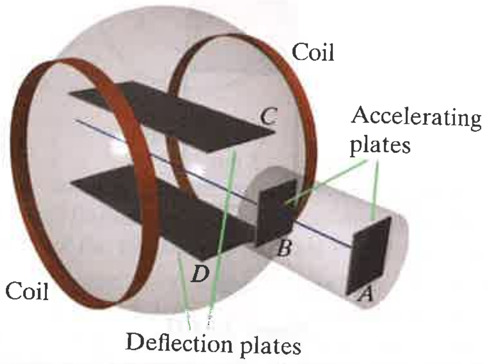

Figure 20.112

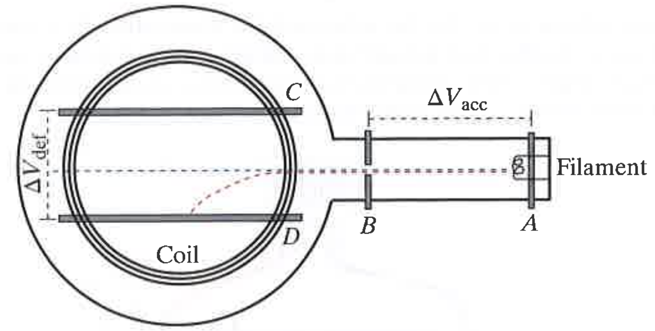

Figure 20.113

When the metal filament gets very hot, electrons occasionally escape from it. These electrons can be accelerated away from the filament by applying a potential difference ΔV_{acc} across the metal plates labeled A and B in the diagram.

The electrons pass through a hole in plate B and enter the glass sphere. There they pass between the two horizontal metal "deflection" plates labeled C and D. A potential difference ΔV_{def} can be applied across these plates, to deflect the beam of electrons.

In front of and in back of the glass sphere are two coils, through which current can be run to produce a magnetic field in the region between the deflection plates. The coils are oriented so that they both produce magnetic fields into the page in this region. **(a)** Which of the accelerating plates, A or B, has a positive charge? **(b)** With no current in the coils, if the potential difference across the deflection plates, V_{def}, is zero, the electrons in the beam travel in a straight line, as indicated in Figure 20.113 by the dashed blue path. However, if V_{def} is not zero, the electron beam is deflected downward, following the path indicated on the diagram by the dashed red line. If the beam follows the dashed red line, what is the direction of the electric field between the deflection plates? **(c)** If a current runs through the coils, there will be a magnetic field in the region between the deflection plates. If the magnetic field made by the coils points into the page in the region between the plates, what is the direction of the magnetic force on an electron in the beam? (You can neglect the effect of the Earth's magnetic field, which is small.) **(d)** The accelerating potential difference ΔV_{acc} is measured to be 3.1 kV. What is the speed of an electron after it passes through the hole in plate B? Each of the two coils has 320 turns. The average radius of the coil is 6 cm. The distance from the center of one coil to the electron beam is 3 cm. If a current of 0.5 A runs through the coils, what is the magnitude of the magnetic field at a location on the axis of the coils, midway between the coils? (The electron beam passes through this location.) When deciding whether to use an exact or an approximate equation here, consider the relative magnitudes of the distances involved. **(e)** In a particular experiment, the accelerating potential difference ΔV_{acc} is set to 3.1 kV. The distance between the deflection plates is 8 mm. A current of 0.5 A runs through the coils, and the potential difference ΔV_{def} is adjusted until the electron beam again follows the straight line path indicated by the dashed blue line. In this situation (electron beam traveling in a straight line), which of the following statements are true? (1) The magnetic force on an electron in the beam is in the direction of its motion. (2) The electric and magnetic forces on an electron in the beam are in opposite directions. (3) The magnitude of the electric field in the region is equal to the magnitude of the magnetic field in the region. (4) The angle between the electric field and the magnetic field in the region is 180°. (5) The net force on an electron in the beam is zero. (6) The electric force on an electron in the beam is equal in magnitude to the magnetic force on the electron. **(f)** What is the value of ΔV_{def} required to make the electron beam travel in a straight line?

••P52 In Figure 20.114 two straight wires carrying conventional current I are connected by a three-quarter-circular arc of radius R_1 and a one-quarter-circular arc of radius R_2. Electric fields are also present in this region, due to charges not shown on the drawing.

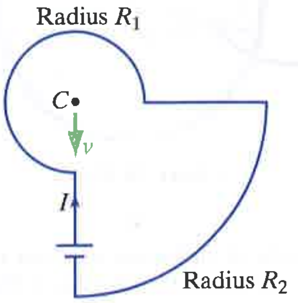

Figure 20.114

An electron is moving down with speed v as it passes through the center C of the arc, and at that instant the net electric and magnetic force on the electron is zero. (The Earth's magnetic field is negligible here.) **(a)** What is the direction of the magnetic field at the center C due to the current I? Explain briefly. **(b)** What is the direction of the electric field at the center C? Explain your reasoning clearly. **(c)** What is the magnitude of the magnetic field at the center C due to the current I? **(d)** What is the magnitude of the electric field at the center C? Explain briefly.

••P53 In Figure 20.115 two long straight wires carrying a large conventional current I are connected by one-and-a-quarter turns of wire of radius R. An electron is moving to the right with speed v at the instant that it passes through the center of the arc. You apply an electric field $\vec{E}$ at the center of the arc in such a way that the net force on the electron at this instant is zero. (You can neglect the gravitational force on the electron, which is easily shown to be negligible, and the magnetic field of the coil is much larger than the magnetic field of the Earth.)

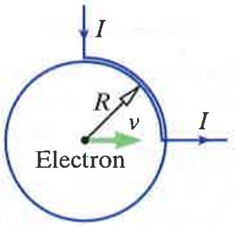

Figure 20.115

Determine the direction and magnitude of the electric field $\vec{E}$. Be sure to explain your work fully; draw and label any vectors you use.

••P54 In Figure 20.116 a battery with known emf $= K$ is connected to two large parallel metal plates. Each plate has a length L and width W, and the plates are a very short distance s apart. The plates are surrounded by a vertical thin circular coil of radius R containing N turns through which runs a steady conventional current I. The center of the coil is at the center of the gap between the plates. At a certain instant, a proton (charge

$+e$, mass M) travels through the center of the coil to the right with speed v, and the net force on the proton at this instant is zero (neglecting the very weak gravitational force). What are the magnitude and direction of conventional current in the coil? Explain clearly.

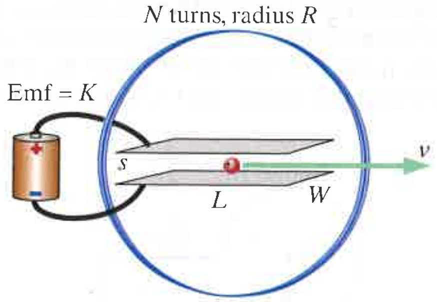

Figure 20.116

Section 20.4

••P55 A slab made of unknown material is connected to a power supply as shown in Figure 20.117. There is a uniform magnetic field of 0.7 T pointing upward throughout this region (perpendicular to the horizontal slab). Two voltmeters are connected to the slab and read steady voltages as shown. The connections across the slab are carefully placed directly across from each other. Assume that there is only one kind of mobile charges in this material, but we don't know whether they are positive or negative.

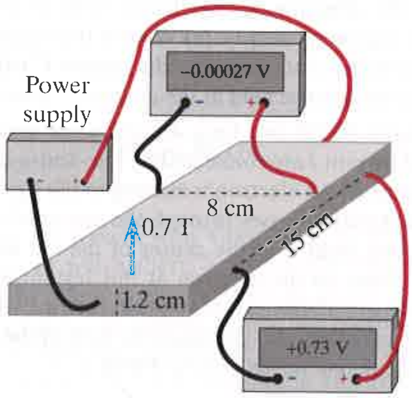

Figure 20.117

(a) Determine the (previously unknown) sign of the mobile charges, and state which way these charges move inside the slab. Explain carefully, using diagrams to support your explanation. **(b)** What is the drift speed $\bar{v}$ of the mobile charges? **(c)** What is the mobility u of the mobile charges? **(d)** The current running through the slab was measured to be 0.3 A. If each mobile charge is singly charged ($|q| = e$), how many mobile charges are there in 1 m^3 of this material? **(e)** What is the resistance in ohms of a 15 cm length of this slab?

••P56 An experiment was carried out to determine the electrical properties of a new conducting material. A bar was made out of the material, 18 cm long with a rectangular cross section 3 cm high and 0.8 cm deep. The bar was part of a circuit and carried a steady current (Figure 20.118 shows only part of the circuit). A uniform magnetic field of 1.5 T was applied perpendicular to the bar, coming out of the page (using some coils that are not shown).

Two voltmeters were connected along and across the bar and read steady voltages as shown (mV = millivolt = 1×10^{-3} V). The connections across the bar were carefully placed directly across from each other to eliminate false readings corresponding to the much larger voltage along the bar. Assume that there is only one kind of mobile charge in this material.

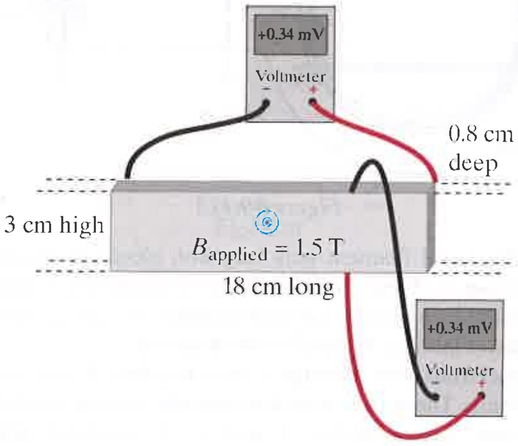

Figure 20.118

(a) What is the sign of the mobile charges, and which way do they move? Explain carefully, using diagrams to support your explanation. **(b)** What is the drift speed v of the mobile charges? Explain your reasoning. **(c)** What is the mobility u of the mobile charges? **(d)** The current running through the bar was measured to be 0.6 A. If each mobile charge is singly charged ($|q| = e$), how many mobile charges are there in 1 m^3 of this material? **(e)** What is the resistance in ohms of this length of bar?

••P57 In Figure 20.119 a bar of length L, width w, and thickness d is positioned a distance h underneath a long straight wire that carries a large but unknown steady current I_{wire} (w is small compared to h, and h is small compared to the length of the long straight wire). The material that the bar is made of is known to have n positive mobile charge carriers ("holes") per cubic meter, each of charge e, and these are the only mobile charge carriers in the bar. An ammeter measures the small current I passing through the bar.

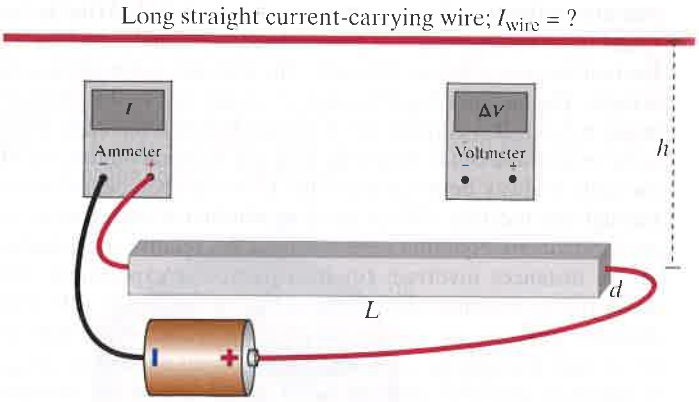

Figure 20.119

(a) Draw connecting wires from the voltmeter to the bar, showing clearly how the ends of the connecting wires must be positioned on the bar in order to permit determining the amount of current in the long straight wire I_{wire}. If the voltmeter reading ΔV is positive, does the current in the long straight wire run to the left or to the right? Explain briefly.

(b) If the voltmeter reading is ΔV, what is the current in the long straight wire, I_{wire}? Express your answer for the large current I_{wire} only in terms of the known quantities: $h, L, w, d, n, I_{\text{ammeter}}$, ΔV, and known physical constants such as e.

••P58 In Figure 20.120 the center of a large bar magnet is 20 cm from a thin plate of high-resistance material 12 cm long, 2.5 cm high, and 0.1 cm thick that is connected to a 240 V power supply whose internal resistance is negligible. The bar magnet is perpendicular to the plate.

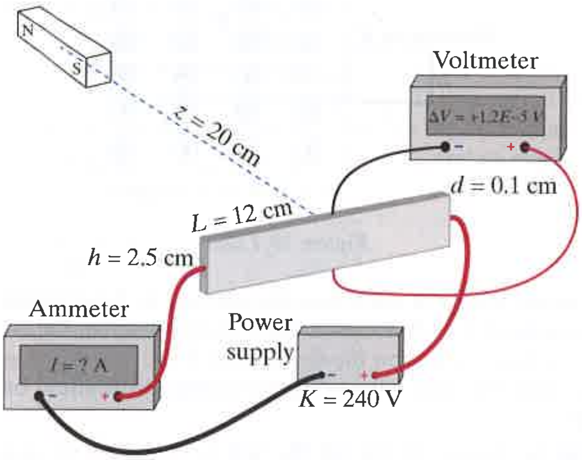

Figure 20.120

The mobility of charge carriers in the thin plate is 3.5×10^{-4} (m/s)/(V/m), and the number density of the singly charged charge carriers is 4×10^{23} m^{-3}. A voltmeter is connected precisely vertically across the thin plate and reads $+1.2 \times 10^{-5}$ V. A low-resistance ammeter is in series with the rest of the circuit. **(a)** Are the charge carriers electrons or holes? Explain, including a physics diagram. **(b)** What is the magnetic dipole moment of the bar magnet? Include units. **(c)** What does the ammeter read, including sign?

••P59 In Figure 20.121 a bar 11 cm long with a rectangular cross section 3 cm high and 2 cm deep is connected to a 1.2 V battery and an ammeter. The resistance of the copper connecting wires and the ammeter, and the internal resistance of the battery, are all negligible compared to the resistance of the bar.

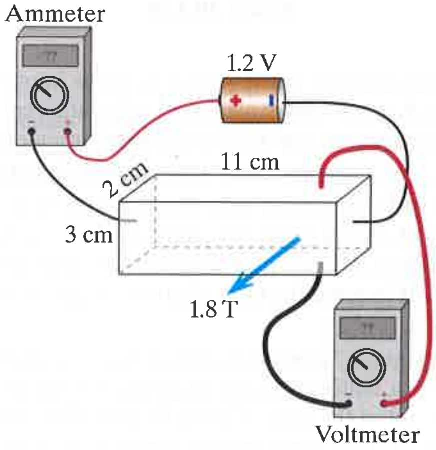

Figure 20.121

Using large coils not shown on the diagram, a uniform magnetic field of 1.8 T was applied perpendicular to the bar (out of the page, as shown). A voltmeter was connected across the bar, with the connections across the bar carefully placed directly across from each other.

The mobile charges in the bar have charge $+e$, their density is $7 \times 10^{23}/\text{m}^3$, and their mobility is 3×10^{-5} (m/s)/(V/m).

Predict the readings of the voltmeter and ammeter, including signs. Explain carefully, using diagrams to support your explanation. Remember that a voltmeter reads positive if the + terminal is connected to higher potential, and that an ammeter reads positive if conventional current enters the + terminal.

Section 20.5

•P60 A neutral iron bar is dragged to the left at speed v through a region with a magnetic field B that points out of the page (Figure 20.122). Which diagram (1–5) best shows the state of the bar?

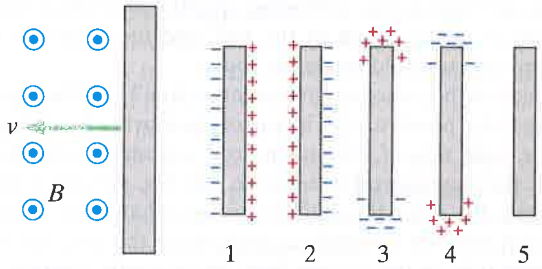

Figure 20.122

•P61 A neutral copper bar oriented horizontally moves upward through a region where there is a magnetic field out of the page. Which diagram (1–5) in Figure 20.123 correctly shows the distribution of charge on the bar?

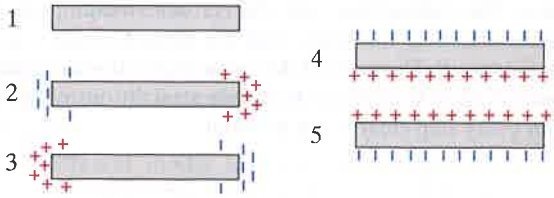

Figure 20.123

•P62 A metal rod of length L slides horizontally at constant speed v on frictionless insulating rails through a region of uniform upward magnetic field of magnitude B (Figure 20.124).

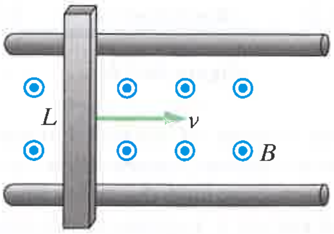

Figure 20.124

On a diagram, show the polarization of the rod and the direction of the Coulomb electric field inside the rod. Explain briefly. What is the magnitude E_C of the Coulomb electric field inside the rod? What is the potential difference across the rod? What is the emf across the rod? What are the magnitude and direction of the force you have to apply to keep the rod moving at a constant speed v?

•P63 A neutral metal rod of length 0.45 m slides horizontally to the left at a constant speed of 7 m/s on frictionless conducting rails through a region of uniform magnetic field of magnitude 0.4 T, directed out of the page as shown in Figure 20.125.

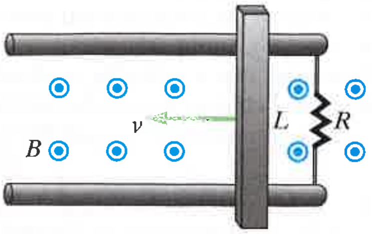

Figure 20.125

Before answering the following questions, draw a diagram showing the polarization of the rod, and the direction of the Coulomb electric field inside the rod.

(a) Which of the following statements is true? (1) The top of the moving rod is positive. (2) The top of the moving rod is negative. (3) The right side of the moving rod is positive. (4) The right side of the moving rod is negative. (5) The moving rod is not polarized. **(b)** After the initial transient, what is the magnitude of the net force on a mobile electron inside the rod? **(c)** What is the magnitude of the electric force on a mobile electron inside the rod? **(d)** What is the magnitude of the magnetic force on a mobile electron inside the rod? **(e)** What is the magnitude of the potential difference across the rod? **(f)** In what direction must you exert a force to keep the rod moving at constant speed?

••P64 A metal bar of mass M and length L slides with negligible friction but with good electrical contact down between two vertical metal posts (Figure 20.126). The bar falls at a constant speed v. The falling bar and the vertical metal posts have negligible electrical resistance, but the bottom rod is a resistor with resistance R. Throughout the entire region there is a uniform magnetic field of magnitude B coming straight out of the page. Explain every step clearly and in detail.

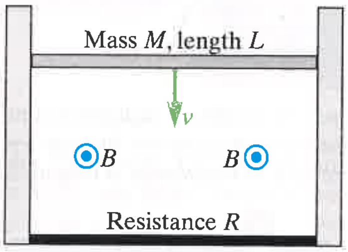

Figure 20.126

(a) Calculate the amount of current I running through the resistor. **(b)** On a diagram, clearly show the surface-charge distribution all the way around the circuit and the direction of the conventional current I. Explain. **(c)** Calculate the constant speed v of the falling bar. **(d)** Show that the rate of change of the gravitational energy of the Universe is equal to the rate of energy dissipated in the resistor.

••P65 In Figure 20.127 a rectangular loop of wire with width w, height h, and resistance R is dragged at constant speed v to the right through a region where there is a uniform magnetic field of magnitude B out of the page. The magnetic field is negligibly small outside that region.

For each stage of the motion, determine the current I in the loop and the force $\vec{F}$ required to maintain the constant speed. There are five stages. **(a)** Before entering the magnetic field region. **(b)** While the loop is part way into the magnetic field region (this is the stage that is shown). **(c)** While the loop is entirely inside the magnetic field region. **(d)** While the loop is part way out of the magnetic field region. **(e)** After leaving the magnetic field region.

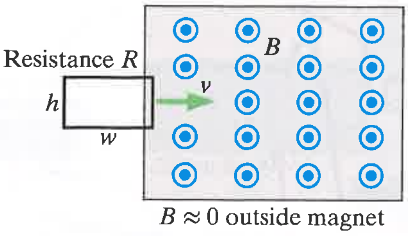

Figure 20.127

Explain briefly in each case. In addition to determining the magnitude of $\vec{F}$ and I for each stage, draw a diagram for each of the five stages and show the direction of $\vec{F}$ and I on the diagram. Also show the approximate surface-charge distribution on the loop.

••P66 In Figure 20.128 on the left is a region of uniform magnetic field B_1 into the page, and adjacent on the right is a region of uniform magnetic field B_2 also into the page. The magnetic field B_2 is smaller than B_1 ($B_2 < B_1$). You pull a rectangular loop of wire of length w, height h, and resistance R from the first region into the second region, on a frictionless surface. While you do this you apply a constant force F to the right, and you notice that the loop doesn't accelerate but moves with a constant speed.

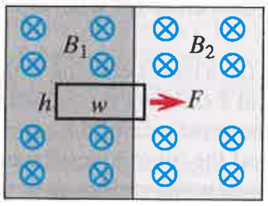

Figure 20.128

Calculate this constant speed v in terms of the known quantities B_1, B_2, w, h, R, and F, and explain your calculation carefully. Also show the approximate surface-charge distribution on the loop.

••P67 A neutral metal rod of length 60 cm falls toward the Earth. The rod is horizontal and oriented east west. **(1)** Which end of the rod, east or west, has excess electrons? Explain, using physics diagrams. **(2)** At a moment when the rod's speed is 4 m/s, approximately how many excess electrons are at the negative end of the rod?

••P68 A "unipolar" generator consists of a copper disk of radius R rotating in a uniform, steady magnetic field B perpendicular to the disk, out of the page (Figure 20.129). (The magnetic field is produced by large coils carrying constant current, not shown in the diagram.) Sliding contacts are made at the center (on the axle) and at the rim of the disk, and the wires are connected to a voltmeter. If the outer rim travels counterclockwise at a speed v, what does the voltmeter read (magnitude and sign)?

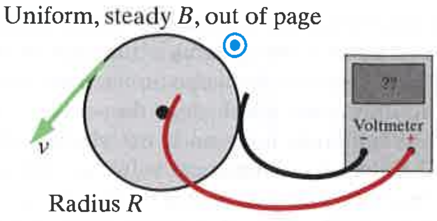

Figure 20.129

••P69 In Figure 20.130 a rectangular loop of wire $L = 15$ cm long by $h = 3$ cm high, with a resistance of $R = 0.3\ \Omega$, moves with constant speed $v = 8$ m/s to the right, emerging from a rectangular region where there is a uniform magnetic field into a region where the magnetic field is negligibly small. In the region of magnetic field, the magnetic field points into the page, and its magnitude is $B = 1.2$ T.

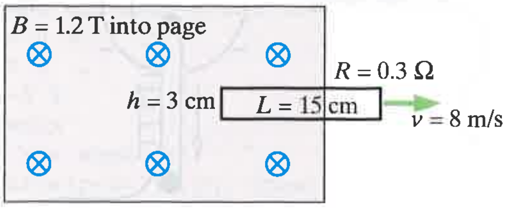

Figure 20.130

(a) On a diagram, show the approximate charge distribution on the moving loop. **(b)** What are the direction and magnitude of conventional current in the loop? Explain briefly. **(c)** Which of the following are true? (1) The magnetic force only stretches the loop; the net magnetic force on the loop is zero. (2) Because a current flows in the loop, there is a magnetic force on the loop. (3) The magnetic force on the loop is in the same direction as the velocity of the loop. **(d)** What are the direction and magnitude of the force that you have to apply in order to make the loop move at its constant speed?

Section 20.6

•P70 A proton moves with speed v in the $+x$ direction. In the lab (stationary) reference frame, what electric and magnetic fields would you observe a distance r above the proton (in the $+y$ direction)? In a reference frame moving with the proton, what electric and magnetic fields would you observe at the same location? Be quantitative.

Section 20.7

•P71 A bar magnet whose magnetic dipole moment is $\langle 4, 0, 1.5\rangle$ $\text{A}\cdot\text{m}^2$ is suspended from a thread in a region where external coils apply a magnetic field of $\langle 0.8, 0, 0\rangle$ T. What is the vector torque that acts on the bar magnet?

•••P72 A bar magnet whose mass is 0.02 kg and whose magnetic dipole moment is $\langle 6, 0, 0\rangle$ $\text{A}\cdot\text{m}^2$ is suspended on a low-friction pivot in a region where external coils apply a magnetic field of $\langle 1.5, 0, 0\rangle$ T. You rotate the bar magnet slightly in the horizontal plane and release it. **(a)** What is the angular frequency of the oscillating magnet? **(b)** What would be the angular frequency if the applied magnetic field were $\langle 3, 0, 0\rangle$ T?

Section 20.8

•P73 A bar magnet whose magnetic dipole moment is 15 $\text{A}\cdot\text{m}^2$ is aligned with an applied magnetic field of 4 T. How much work must you do to rotate the bar magnet 180° to point in the direction opposite to the magnetic field?

•P74 The center of a bar magnet whose magnetic dipole moment is $\langle 8, 0, 0\rangle$ $\text{A}\cdot\text{m}^2$ is located at the origin. A second bar magnet whose magnetic dipole moment is $\langle 3, 0, 0\rangle$ $\text{A}\cdot\text{m}^2$ is located at $x = 0.12$ m. What is the vector force on the second magnet due to the first magnet?

Section 20.9

•P75 A thin rectangular coil 8 cm by 5 cm has 50 turns of copper wire. It is made to rotate with angular frequency 100 rad/s in a magnetic field of 1.2 T. **(a)** What is the maximum emf produced in the coil? **(b)** What is the maximum power delivered to a 50 ohm resistor?

Section 20.10

•P76 In order for a spark to occur, it is necessary to ionize the air, which is not usually a conductor. One possible model for the process by which air becomes ionized is this: if a sufficiently strong electric field were applied to an atom, it would be possible to pull an outer electron out of the atom, leaving a positively charged ion and a free electron. We will estimate the strength of the electric field required to pull an electron out of an atom. **(a)** Consider the interaction of a single outer electron in a nitrogen atom with the "atomic core" (all the other charged particles in the atom—the protons in the nucleus and all the other electrons). What is the net charge of the atomic core? **(b)** If the radius of the atom is approximately 1×10^{-10} m, what is the magnitude of the electric field due to the atomic core at the location of the outer electron? **(c)** What is the magnitude of the electric field you would have to apply in order to pull the outer electron out of the atom? **(d)** It is observed experimentally that an applied electric field of 3×10^6 V/m is sufficient to cause a spark in air. What is the ratio of the electric field you calculated to the observed field needed to start a spark? **(e)** What should we conclude about this model? (1) Using more significant figures would not improve the agreement. (2) We need to think of a different physical explanation of how air gets ionized. (3) If our calculation used more accurate values the numbers would probably agree. (4) Since the discrepancy is so large, this model must be wrong.

•P77 A different model for how air becomes ionized in a spark focuses on energy. Suppose that a very energetic particle collided with a nitrogen or oxygen atom and knocked out an electron, ionizing the molecule. Estimate the kinetic energy required for this process. **(a)** Consider an outer electron in a nitrogen atom, interacting with the atomic core (nucleus plus all other electrons). What is the net charge of the atomic core? **(b)** Assuming the radius of the nitrogen atom is about 1×10^{-10} m, what is the electric potential at the location of this outer electron? **(c)** Ionizing the atom means moving the outer electron a very large distance away from the atomic core. What is the electric potential a very large distance from the atomic core? **(d)** What is the potential difference between these two locations? **(e)** What is the change in electric potential energy of the system of the electron plus the atomic core in this process? **(f)** How much kinetic energy would an incoming particle need in order to ionize the atom in a collision between the particle and the atom?

•P78 We will consider the possibility that a free electron acted on by an electric field could gain enough energy to ionize an air molecule in a collision. **(a)** Consider an electron that starts from rest in a region where there is an electric field (due to some charged objects nearby) whose magnitude is nearly constant. If the electron travels a distance d and the magnitude of the electric field is E, what is the potential difference through which the electron travels? (Pay attention to signs: Is the electron traveling with the electric field or opposite to the electric field?) **(b)** What is the change in potential energy of the system in this process? **(c)** What is the change in the kinetic energy of the electron in this process? **(d)** We found the mean free path of an electron in air to be about 5×10^{-7} m, and in the previous question you calculated the energy required to knock an electron out of an atom. What is the magnitude of the electric field that would be required in order for an electron to gain sufficient kinetic energy to ionize a nitrogen molecule? **(e)** The electric field required to cause a spark in air is observed to be about 3×10^6 V/m at STP. What is the ratio of the magnitude of the field you calculated in the previous part to the observed value at STP? **(f)** What is it reasonable to conclude about this model of how air becomes ionized? (1) Since we used accurate numbers, this is a huge discrepancy, and the model is wrong. (2) Considering the approximations we made, this is pretty good agreement, and the model may be correct.

•P79 Explain briefly why there is a limit to how much charge can be placed on a metal sphere in the classroom. If the radius of the sphere is 15 cm, what is the maximum amount of charge you can place on the sphere? (Remember that a uniform sphere of charge makes an electric field outside the sphere as though all the charge were concentrated at the center of the sphere.)

••P80 A Van de Graaff generator pulls electrons out of the Earth and transports them on a conveyor belt onto a nearly spherical metal shell (Figure 20.131). The diameter of this generator's metal shell is 24 cm.

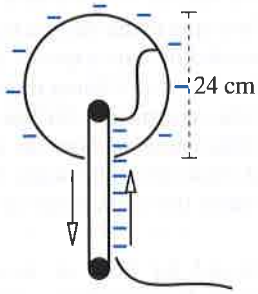

Figure 20.131

(a) Suppose that the conveyor belt in the Van de Graaff generator is running so fast that the generator succeeds in building up and maintaining just enough charge on the metal shell to cause the air to steadily glow bluish near the surface of the shell. Under these conditions, how much net charge $|Q|$ is on the metal shell? Calculate a numerical value for $|Q|$ and explain briefly. (Remember that the electric field outside a uniformly charged sphere is like that of a point charge located at the center of the sphere.) **(b)** Under these conditions (with the air steadily glowing), the Van de Graaff generator continually delivers additional electrons to the metal shell and yet the net charge Q on the shell does not change. Explain briefly but in detail why the charge on the shell does not change.

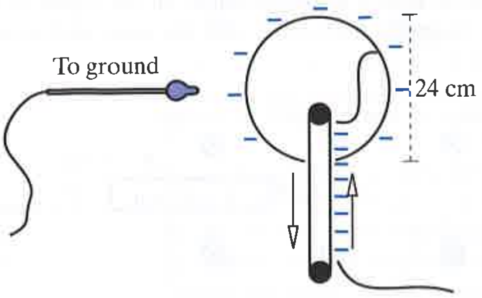

Figure 20.132

(c) Now assume that the Van de Graaff generator is run more slowly, and the buildup of charge on the metal shell is limited by the inability of the motor to force any more electrons onto the negatively charged shell. The air no longer glows. We have a pear-shaped piece of metal that is attached by a metal wire to the earth (grounded). When we bring the grounded piece of metal to a location near the Van de Graaff metal shell, as shown in Figure 20.132, we observe a big spark. Explain why a spark occurs now but doesn't occur without the additional piece of metal nearby. **(d)** This spark lasts only a very short time. Why? **(e)** If we keep holding the grounded piece of metal 5 cm from the metal shell, we observe that there are big, brief sparks every 2 s. If we reduce the distance to 2 cm, the sparks that we observe occur more frequently, and they are less intense. Explain briefly.

COMPUTATIONAL PROBLEMS

••P81 Starting with the skeleton program given below, write a program to predict the motion of a proton in a constant magnetic field. The skeleton program draws a "floor" and displays a uniform magnetic field, which initially has the value $\langle 0, 0.2, 0 \rangle$ T. Before beginning it may be helpful to review a previous program in which you predicted the motion of an object under the influence of one or more forces. Recall that you must:

Repeat

- Calculate the net force $\vec{F}_{\text{net}}$ acting on the system.
- Update the momentum of the system: $\vec{p}_f = \vec{p}_i + \vec{F}_{\text{net}}\,\Delta t$.
- Update the position: $\vec{r}_f = \vec{r}_i + \vec{v}_{\text{avg}}\,\Delta t$.

Use $\vec{p}_f/m$ to approximate the $\vec{v}_{\text{avg}}$ in each step.

Once your program is working, do the following: **(a)** Using an initial velocity of $\langle 2 \times 10^6, 0, 0 \rangle$ m/s, change the `while` statement to `while t < 3.34e-7:` and run the program. The proton should just make one complete orbit; if it does not, review your code. **(b)** What is the approximate radius of the proton's path? **(c)** What happens to the radius of the path if you double the initial speed? **(d)** How does doubling the speed change the time to complete one orbit? **(e)** What happens to the radius of the path if you halve the initial speed of 2×10^6 m/s? **(f)** How does halving the speed change the time to complete one orbit? **(g)** Restore the proton's initial velocity to its original value, and double the magnetic field. What changes? **(h)** Restore the magnetic field to its original value. Change the proton's initial velocity so that it is parallel to the magnetic field. Describe the path followed by the proton, and explain. **(i)** Change the initial velocity back to its original value, then add a significant $+y$ component to the velocity. Increase the time allowed in the loop sufficiently to allow the proton to make five complete orbits. Describe the proton's path, and explain. **(j)** Change the proton to an antiproton, whose mass is the same as that of the proton, but whose charge is $-e$. What changes?

```
from visual import *
scene.width = 800
scene.height = 800
## CONSTANTS ##
mzofp = 1e-7  ## mu-zero-over-four-pi
qe = 1.6e-19
mproton = 1.7e-27
B0 = vector(0,0.2,0)
bscale = 1
#### THIS CODE DRAWS A GRID ##
#### AND DISPLAYS MAGNETIC FIELD ##
xmax = 0.4
dx = 0.1
yg = -0.1
x = -xmax
while x < xmax+dx:
    curve(pos=[(x,yg,-xmax),(x,yg,xmax)],
          color=(.7,.7,.7))
    x = x + dx
z = -xmax
while z < xmax+dx:
    curve(pos=[(-xmax,yg,z),(xmax,yg,z)],
          color=(.7,.7,.7))
    z = z + dx
x = -xmax
dx = 0.2
while x < xmax+dx:
    z = -xmax
    while z < xmax+dx:
        arrow(pos=(x,yg,z),
              axis=B0*bscale,
              color=(0,.8,.8))
        z = z + dx
    x = x + dx
#### OBJECTS AND INITIAL CONDITIONS ##
particle = sphere(pos=vector(0,0.15,0.3),
                  radius=1e-2,
                  color=color.yellow,
                  make_trail=True)
## make trail easier to see (thicker) ##
particle.trail_object.radius = particle.
radius/3
vparticle = vector(-2e6,0,0)
p = mproton*vparticle
qparticle = qe
deltat = 5e-11
t = 0
############################################
while True:
    rate(500)
    ## YOUR CODE GOES HERE ##
```

•••P82 Write a computer program to compute and display the motion of a proton inside a cyclotron (see Section 20.1). The first cyclotrons were small desktop devices; we will model a small device in order to understand the basic physical phenomena. Consider a cyclotron whose radius is 5 cm, with a gap of 0.5 cm between the dees (Figure 20.133).

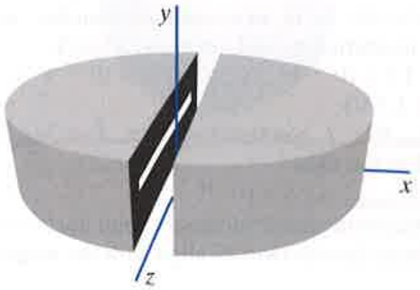

Figure 20.133

External magnets create a uniform magnetic field of 1.0 T in the $+y$ direction throughout the device. A proton starts essentially from rest at the center of the cyclotron. The maximum potential difference between the dees is 5000 V. Note that the electric field inside the dees is 0 at all times. Figure 20.133 shows that the metal dees form a nearly closed conducting enclosure.
(a) What is the angular frequency ω of the sinusoidally oscillating potential difference you will need to apply? **(b)** Compute and display the trajectory of a proton in the cyclotron; display the trail of the proton. You may assume that the proton does not reach a speed sufficiently close to the speed of light to require a relativistically correct calculation, but do check this assumption. To get your program going, you can use a large value of dt (such as 1E-10 s), but you will need to decrease this value later. **(c)** Plot the proton's kinetic energy K (in eV) vs. time. Explain the shape of the graph you observe. **(d)** What happens if you use a different angular frequency for the potential difference? For example, try an angular frequency of 0.6ω. **(e)** If the proton gains a significant amount of kinetic energy while inside the dees, your dt is too large. Adjust your dt appropriately. What value of dt gives reasonable results? **(f)** How much time does the proton take to reach the outer edge of the cyclotron? **(g)** What is K (in eV) when the proton reaches the outer edge of the cyclotron? **(h)** Given your answer to (g), how many orbits must the proton have made before reaching the outer edge of the cyclotron? **(i)** What is the final speed of the proton? Were you justified in assuming that $v \ll c$?