1. (b). The force that a magnetic field exerts on a charged particle moving through it is given by \( F = qvB \sin \theta = qvB_z \), where \( B_z \) is the component of the field perpendicular to the particle's velocity. Since the particle moves in a straight line, the magnetic force (and hence \( B_z \), since \( qv \neq 0 \)) must be zero.

2. (c). The magnetic force exerted by a magnetic field on a charge is proportional to the charge's velocity relative to the field. If the charge is stationary, as in this situation, there is no magnetic force.

3. (c). The torque that a planar current loop will experience when it is in a magnetic field is given by \( \tau = BlA \sin \theta \). Note that this torque depends on the strength of the field, the current in the coil, the area enclosed by the coil, and the orientation of the plane of the coil relative to the direction of the field. However, it does not depend on the shape of the loop.

4. (a). The magnetic force acting on the particle is always perpendicular to the velocity of the particle, and hence to the displacement the particle is undergoing. Under these conditions, the force does no work on the particle and the particle’s kinetic energy remains constant.

5. (a) and (c). The magnitude of the force per unit length between two parallel current carrying wires is \( F/\ell = (\mu_0 I)(I)/(2\pi d) \). The magnitude of this force can be doubled by doubling the magnitude of the current in either wire. It can also be doubled by decreasing the distance between them, \( d \), by half. Thus, both choices (a) and (c) are correct.

6. (b). The two forces are an action-reaction pair. They act on different wires and have equal magnitudes but opposite directions.
ANSWERS TO MULTIPLE CHOICE QUESTIONS

1. The electron moves in a horizontal plane in a direction of 35° N or E, which is the same as 55° E of N. Since the magnetic field at this location is horizontal and directed due north, the angle between the direction of the electron’s velocity and the direction of the magnetic field is 55°. The magnitude of the magnetic force experienced by the electron is then

\[ F = qvB\sin\theta = \left(1.6 \times 10^{-19} \text{ C}\right)\left(2.5 \times 10^4 \text{ m/s}\right)\left(0.10 \times 10^{-4} \text{ T}\right)\sin 55° = 3.3 \times 10^{-18} \text{ N} \]

The right-hand rule number 1 predicts a force directed upward, away from the Earth’s surface for a positively charged particle moving in the direction of the electron. However, the negatively charged electron will experience a force in the opposite direction, downward toward the Earth’s surface. Thus, the correct choice is (d).

2. If the magnitude of the magnetic force on the wire equals the weight of the wire, then

\[ BI\sin\theta = w, \text{ or } B = \frac{w}{Il}\sin\theta \]

The magnitude of the magnetic field is a minimum when \( \theta = 90° \) and \( \sin\theta = 1 \). Thus,

\[ B_{\text{min}} = \frac{w}{Il} = \frac{1.0 \times 10^{-2} \text{ N}}{(0.10 \text{ A})(0.50 \text{ m})} = 0.20 \text{ T} \]

and (a) is the correct answer for this question.

3. The \( z \)-axis is perpendicular to the plane of the loop, and the angle between the direction of this normal line and the direction of the magnetic field is \( \theta = 30.0° \). Thus, the magnitude of the torque experienced by this coil containing \( N = 10 \) turns is

\[ \tau = BIOn\sin\theta = \left(0.010 \text{ T}\right)(2.0 \text{ A})\left[\left(0.20 \text{ m}\right)(0.30 \text{ m}\right)(10)\sin 30.0° = 6.0 \times 10^{-3} \text{ N} \cdot \text{m} \]

meaning that (c) is the correct answer.

4. A charged particle moving perpendicular to a magnetic field experiences a centripetal force of magnitude \( F_c = mv^2/r = qvB \) and follows a circular path of radius \( r = mv/qB \). The speed of this proton must be

\[ v = \frac{qBr}{m} = \frac{\left(1.6 \times 10^{-19} \text{ C}\right)(0.050 \text{ T})(1.0 \times 10^{-3} \text{ m})}{1.67 \times 10^{-27} \text{ kg}} = 4.8 \times 10^3 \text{ m/s} \]

and choice (e) is the correct answer.

5. The magnitude of the magnetic field at distance \( r \) from a long straight wire carrying current \( I \) is \( B = \mu_0I/2\pi r \). Thus, for the described situation,

\[ B = \frac{\left(4\pi \times 10^{-7} \text{ T} \cdot \text{m/A}\right)(1 \text{ A})}{2\pi(2 \text{ m})} = 1 \times 10^{-7} \text{ T} \]

making (d) the correct response.

6. The force per unit length between this pair of wires is

\[ F = \frac{\mu_0I_1I_2}{2\pi d} = \frac{\left(4\pi \times 10^{-7} \text{ T} \cdot \text{m/A}\right)(3 \text{ A})^2}{2\pi(2 \text{ m})} = 9 \times 10^{-7} \text{ N} = 1 \times 10^{-6} \text{ N} \]

and (d) is the best choice for this question.

7. The magnitude of the magnetic field inside the specified solenoid is

\[ B = \mu_0NI = \mu_0 \left(\frac{N}{l}\right)I = \left(4\pi \times 10^{-7} \text{ T} \cdot \text{m/A}\right)\left(\frac{120}{0.50 \text{ m}}\right)(2.0 \text{ A}) = 6.0 \times 10^{-4} \text{ T} \]

which is choice (e).
The magnitude of the magnetic force experienced by a charged particle in a magnetic field is given by $F = qvB\sin\theta$, where $v$ is the speed of the particle and $\theta$ is the angle between the direction of the particle’s velocity and the direction of the magnetic field. If either $v = 0$ [choice (e)] or $\sin\theta = 0$ [choice (c)], this force has zero magnitude. All other choices are false, so the correct answers are (c) and (e).

The force that a magnetic field exerts on a moving charge is always perpendicular to both the direction of the field and the direction of the particle’s motion. Since the force is perpendicular to the direction of motion, it does no work on the particle and hence does not alter its speed. Because the speed is unchanged, both the kinetic energy and the magnitude of the linear momentum will be constant. Correct answers among the list of choices are (d) and (e). All other choices are false.

By the right-hand rule number 1, when the proton first enters the field, it experiences a force directed upward, toward the top of the page. This will deflect the proton upward, and as the proton’s velocity changes direction, the force changes direction always staying perpendicular to the velocity. The force, being perpendicular to the motion, causes the particle to follow a circular path, with no change in speed, as long as it is in the field. After completing a half circle, the proton will exit the field traveling toward the left. The correct answer is choice (d).

The contribution made to the magnetic field at point $P$ by the lower wire is directed out of the page, while the contribution due to the upper wire is directed into the page. Since point $P$ is equidistant from the two wires, and the wires carry the same magnitude currents, these two oppositely directed contributions to the magnetic field have equal magnitudes and cancel each other. Therefore, the total magnetic field at point $P$ is zero, making (a) the correct answer for this question.

The magnetic field due to the current in the vertical wire is directed into the page on the right side of the wire and out of the page on the left side. The field due to the current in the horizontal wire is out of the page above this wire and into the page below the wire. Thus, the two contributions to the total magnetic field have the same directions at points B (both out of the page) and D (both contributions into the page), while the two contributions have opposite directions at points A and C. The magnitude of the total magnetic field will be greatest at points B and D where the two contributions are in the same direction, and smallest at points A and C where the two contributions are in opposite directions and tend to cancel. The correct choices for this question are (a) and (c).

Any point in region I is closer to the upper wire which carries the larger current. At all points in this region, the outward directed field due the upper wire will have a greater magnitude than will the inward directed field due to the lower wire. Thus, the resultant field in region I will be nonzero and out of the page, meaning that choice (d) is a true statement and choice (a) is false. In region II, the field due to each wire is directed into the page, so their magnitudes add and the resultant field cannot be zero at any point in this region. This means that choice (b) is false. In region III, the field due to the upper wire is directed into the page while that due to the lower wire is out of the page. Since points in this region are closer to the wire carrying the smaller current, there are points in this region where the magnitudes of the oppositely directed fields due to the two wires will have equal magnitudes, canceling each other and producing a zero resultant field. Thus, choice (c) is true and choice (e) is false. The correct answers for this question are choices (c) and (d).

The torque exerted on a single turn coil carrying current $I$ by a magnetic field $B$ is $\tau = BIA\sin\theta$. The line perpendicular to the plane of each coil is also perpendicular to the direction of the magnetic field (i.e., $\theta = 90^\circ$). Since $B$ and $I$ are the same for all three coils, the torques exerted on them are proportional to the area $A$ enclosed by each of the coils. Coil A is rectangular with area $A_A = (1 \text{ m})(2 \text{ m}) = 2 \text{ m}^2$. Coil B is elliptical with semi-major axis $a = 0.75 \text{ m}$ and
semi-minor axis $b = 0.5 \text{ m}$, giving an area $A_b = \pi ab$ or $A_b = \pi (0.75 \text{ m})(0.5 \text{ m}) = 1.2 \text{ m}^2$.

Coil C is triangular with area $A_c = \frac{1}{2} (\text{base})(\text{height})$, or $A_c = \frac{1}{2} (1 \text{ m})(3 \text{ m}) = 1.5 \text{ m}^2$. Thus, $A_A > A_c > A_b$, meaning that $\tau_A > \tau_c > \tau_b$ and choice (b) is the correct answer.

15. According to right-hand rule number 2, the magnetic field at point $P$ due to the current in the wire is directed out of the page, meaning that choices (c) and (e) are false. The magnitude of this field is given by $B = \mu I/2\pi r$, so choices (b) and (d) are false. Choice (a) is correct about both the magnitude and direction of the field and is the correct answer for the question.

16. The magnetic field inside a solenoid, carrying current $I$, with $N$ turns and length $L$, is

$$B = \mu B_L = \mu \left( \frac{N}{L} \right) I.$$ Thus, $B_A = \mu_0 N_A I / L_A$, $B_h = \mu_0 N_A I / 2L_A = \frac{1}{2} B_A$, and $B_C = \mu_0 (2N_A) I / L_A / 2 = 4B_A$.

Therefore, we see that $B_C > B_A > B_h$, and choice (d) gives the correct rankings.

ANSWERS TO EVEN NUMBERED CONCEPTUAL QUESTIONS

2. No. The force that a constant magnetic field exerts on a charged particle is dependent on the velocity of that particle. If the particle has zero velocity, it will experience no magnetic force and cannot be set in motion by a constant magnetic field.

4. Straight down toward the surface of Earth.

6. The magnet causes domain alignment in the iron such that the iron becomes magnetic and is attracted to the original magnet. Now that the iron is magnetic, it can produce an identical effect in another piece of iron.

8. The magnet produces domain alignment in the nail such that the nail is attracted to the magnet. Regardless of which pole is used, the alignment in the nail is such that it is attracted to the magnet.

10. No. The magnetic field created by a single current loop resembles that of a bar magnet — strongest inside the loop, and decreasing in strength as you move away from the loop. Neither is the field uniform in direction — the magnetic field lines loop through the loop.

12. Near the poles the magnetic field of Earth points almost straight downward (or straight upward), in the direction (or opposite to the direction) the charges are moving. As a result, there is little or no magnetic force exerted on the charged particles at the pole to deflect them away from Earth.

14. The loop can be mounted on an axle that can rotate. The current loop will rotate when placed in an external magnetic field for some arbitrary orientation of the field relative to the loop. As the current in the loop is increased, the torque on it will increase.

16. (a) The blue magnet experiences an upward magnetic force equal to its weight. The yellow magnet is repelled by the red magnets by a force whose magnitude equals the weight of the yellow magnet plus the magnitude of the reaction force exerted on this magnet by the blue magnet.

(b) The rods prevent motion to the side and prevent the magnets from rotating under their mutual torques. Its constraint changes unstable equilibrium into stable.

c) Most likely, the disks are magnetized perpendicular to their flat faces, making one face a north pole and the other a south pole. The yellow magnet has a pole on its lower face which
is the same as the pole on the upper faces of the red magnets. The pole on the lower face of the blue magnet is the same as that on the upper face of the yellow magnet.

(d) If the upper magnet were inverted the yellow and blue magnets would attract each other and stick firmly together. The yellow magnet would continue to be repelled by and float above the red magnets.

PROBLEM SOLUTIONS

19.1 Consider a three-dimensional coordinate system with the $xy$ plane in the plane of this page, the $+x$-direction toward the right edge of the page and the $+y$-direction toward the top of the page. Then, the $z$-axis is perpendicular to the page with the $+z$-direction being upward, out of the page. The magnetic field is directed in the $+x$-direction, toward the right.

(a) When a proton (positively charged) moves in the $+y$-direction, the right-hand rule number 1 gives the direction of the magnetic force as into the page or in the $-z$-direction.

(b) With $\vec{v}$ in the $-y$-direction, the right-hand rule number 1 gives the direction of the force on the proton as out of the page, in the $+z$-direction.

(c) When the proton moves in the $+x$-direction, parallel to the magnetic field, the magnitude of the magnetic force it experiences is $F = qvB \sin(0^\circ) = 0$, or there is a zero force in this case.

19.2 (a) For a positively charged particle, the direction of the force is that predicted by the right-hand rule number one. These are:

(a') in plane of page and to left  (b') into the page

(c') out of the page  (d') in plane of page and toward the top

(e') into the page  (f') out of the page

(b) For a negatively charged particle, the direction of the force is exactly opposite what the right-hand rule number 1 predicts for positive charges. Thus, the answers for part (b) are reversed from those given in part (a).

19.3 Since the particle is positively charged, use the right-hand rule number 1. In this case, start with the fingers of the right hand in the direction of $\vec{v}$ and the thumb pointing in the direction of $\vec{F}$. As you start closing the hand, the fingers point in the direction of $\vec{B}$ after they have moved $90^\circ$. The results are

(a) into the page  (b) toward the right  (c) toward bottom of page

19.4 Hold the right hand with the fingers in the direction of $\vec{v}$ so that as you close your hand, the fingers move toward the direction of $\vec{B}$. The thumb will point in the direction of the force (and hence the deflection) if the particle has a positive charge. The results are

(a) toward top of page  (b) out of the page, since the charge is negative.

(c) $\theta = 180^\circ \Rightarrow$ zero force  (d) into the page
19.5 (a) The proton experiences maximum force when it moves perpendicular to the magnetic field, and the magnitude of this maximum force is

\[ F_{\text{max}} = qvB \sin 90^\circ = (1.60 \times 10^{-19} \text{ C})(6.00 \times 10^6 \text{ m/s})(1.50 \text{ T})(1) = 1.44 \times 10^{-12} \text{ N} \]

(b) \[ a_{\text{max}} = \frac{F_{\text{max}}}{m_p} = \frac{1.44 \times 10^{-12} \text{ N}}{1.67 \times 10^{-31} \text{ kg}} = 8.62 \times 10^{19} \text{ m/s}^2 \]

(c) Since the magnitude of the charge of an electron is the same as that of a proton, the force experienced by the electron would have the same magnitude, but would be in the opposite direction due to the negative charge of the electron. The acceleration of the electron would be much greater than that of the proton because of the mass of the electron is much smaller.

19.6 From \( F = qvB \sin \theta \), the magnitude of the force is found to be

\[ F = (1.60 \times 10^{-19} \text{ C})(6.2 \times 10^6 \text{ m/s})(50.0 \times 10^{-6} \text{ T})\sin(90.0^\circ) = 4.96 \times 10^{-12} \text{ N} \]

Using the right-hand rule (fingers point westward in direction of \( v \), so they move downward toward the direction of \( \mathbf{B} \) as you close the hand, the thumb points southward. Thus, the direction of the force exerted on a proton (a positive charge) is \textbf{toward the south}.

19.7 The gravitational force is small enough to be ignored, so the magnetic force must supply the needed centripetal acceleration. Thus,

\[ \frac{m v^2}{r} = qvB \sin 90^\circ, \text{ or } v = \frac{q R}{m} \text{ where } r = R_e + 1000 \text{ km} = 7.38 \times 10^8 \text{ m} \]

\[ v = \frac{(1.60 \times 10^{-19} \text{ C})(4.00 \times 10^{-4} \text{ T})(7.38 \times 10^8 \text{ m})}{1.67 \times 10^{-27} \text{ kg}} = 2.83 \times 10^7 \text{ m/s} \]

If \( v \) is \textbf{toward the west} and \( \mathbf{B} \) is northward, \( \mathbf{F} \) will be directed downward as required.

19.8 The speed attained by the electron is found from \( \frac{1}{2} m v^2 = q|\Delta V| \), or

\[ v = \sqrt{\frac{2 q|\Delta V|}{m}} = \sqrt{\frac{2(1.60 \times 10^{-19} \text{ C})(2.400 \text{ V})}{9.11 \times 10^{-31} \text{ kg}}} = 2.90 \times 10^7 \text{ m/s} \]

(a) Maximum force occurs when the electron enters the region perpendicular to the field.

\[ F_{\text{max}} = qvB \sin 90^\circ = (1.60 \times 10^{-19} \text{ C})(2.90 \times 10^7 \text{ m/s})(1.70 \text{ T}) = 7.90 \times 10^{-12} \text{ N} \]

(b) Minimum force occurs when the electron enters the region parallel to the field.

\[ F_{\text{min}} = qvB \sin 0^\circ = 0 \]
19.9  The magnitude of the magnetic force acting on the electron is \( F = qvB \sin 90^\circ = ma \), so the magnitude of the magnetic field is given by

\[
B = \frac{ma}{ev} = \frac{(9.11 \times 10^{-31} \text{ kg}) (4.0 \times 10^{16} \text{ m/s}^2)}{(1.60 \times 10^{-19} \text{ C})(1.5 \times 10^{-7} \text{ m/s})} = 1.5 \times 10^{-7} \text{ T}
\]

To determine the direction of the field, employ a variation of right-hand rule number 1. Hold your right hand flat with the fingers extended in the direction of the electron’s velocity (toward the top of the page) and the thumb in the direction of the magnetic force (toward the right edge of the page). Then, as you close your hand, the fingers will point out of the page after they have moved 90°. This would be the correct direction for the magnetic field if the particle were positively charged. Since the electron is a negative particle, the actual direction of the field is opposite that predicted by the right-hand rule, or it is directed into the page (the \( z \)-direction).

19.10  The force on a single ion is

\[
F_i = qvB \sin \theta = (1.60 \times 10^{-19} \text{ C})(0.851 \text{ m/s})(0.254 \text{ T}) \sin (51.0^\circ) = 2.69 \times 10^{-20} \text{ N}
\]

The total number of ions present is

\[
N = \left( 3.00 \times 10^{30} \text{ ions/cm}^3 \right) \left( 100 \text{ cm}^3 \right) = 3.00 \times 10^{22}
\]

Thus, assuming all ions move in the same direction through the field, the total force is

\[
F = N \cdot F_i = \left( 3.00 \times 10^{22} \right) \left( 2.69 \times 10^{-20} \text{ N} \right) = 806 \text{ N}
\]

19.11  Gravitational force:

\[
F_g = mg = (9.11 \times 10^{-31} \text{ kg})(9.80 \text{ m/s}^2) = 8.93 \times 10^{-30} \text{ N downward}
\]

Electric force:

\[
F_e = qE = (-1.60 \times 10^{-19} \text{ C})(-100 \text{ N/C}) = 1.60 \times 10^{-17} \text{ N upward}
\]

Magnetic force:

\[
F_m = qvB \sin \theta = (-1.60 \times 10^{-19} \text{ C})(6.00 \times 10^4 \text{ m/s})(50.0 \times 10^4 \text{ T}) \sin (90.0^\circ)
\]

\[
= 4.80 \times 10^{-17} \text{ N in direction opposite right hand rule prediction}
\]

\[
F_m = 4.80 \times 10^{-17} \text{ N downward}
\]

19.12  Hold the right hand with the fingers in the direction of the current so, as you close the hand, the fingers move toward the direction of the magnetic field. The thumb then points in the direction of the force. The results are

(a) to the left  (b) into the page  (c) out of the page

(d) toward top of page  (e) into the page  (f) out of the page
**Chapter 19**

19.13 From \( F = B I L \sin \theta \), the magnetic field is

\[
B = \frac{F}{I L \sin \theta} = \frac{0.12 \text{ N/m}}{15 \text{ A} \sin 90^\circ} = 8.0 \times 10^{-3} \text{ T}
\]

The direction of \( \vec{B} \) must be **the +z-direction** to have \( \vec{F} \) in the –y-direction when \( \vec{I} \) is in the +x-direction.

19.14 (a) \( F = B I L \sin \theta = (0.28 \text{ T})(3.0 \text{ A})(0.14 \text{ m}) \sin 90^\circ = 0.12 \text{ N} \)

(b) **Neither the direction of the magnetic field nor that of the current is given.** Both must be known before the direction of the force can be determined. In this problem, you can only say that the force is perpendicular to both the wire and the field.

19.15 Use the right-hand rule number 1, holding your right hand with the fingers in the direction of the current and the thumb pointing in the direction of the force. As you close your hand, the fingers will move toward the direction of the magnetic field. The results are

(a) **into the page**  
(b) **toward the right**  
(c) **toward the bottom of the page**

19.16 In order to just lift the wire, the magnetic force exerted on a unit length of the wire must be directed upward and have a magnitude equal to the weight per unit length. That is, the magnitude is

\[
\frac{F}{\ell} = B I \sin \theta = \left( \frac{m}{\ell} \right) g \quad \text{giving} \quad B = \left( \frac{m}{\ell} \right) \frac{g}{I \sin \theta}
\]

To find the minimum possible field, the magnetic field should be perpendicular to the current \( (\theta = 90.0^\circ) \). Then,

\[
B_{\text{min}} = \left( \frac{m}{\ell} \right) \frac{g}{I \sin 90.0^\circ} = \left[ 0.500 \text{ g/cm} \left( \frac{1 \text{ kg}}{10^2 \text{ g}} \right) \left( \frac{10^2 \text{ cm}}{1 \text{ m}} \right) \right] \left( 9.80 \text{ m/s}^2 \right) (2.00 \text{ A})(1) = 0.245 \text{ T}
\]

To find the direction of the field, hold the right hand with the thumb pointing upward (direction of the force) and the fingers pointing southward (direction of current). Then, as you close the hand, the fingers point eastward. The magnetic field should be directed **eastward**.

19.17 \( F = B I L \sin \theta = (0.300 \text{ T})(10.0 \text{ A})(5.00 \text{ m}) \sin 30.0^\circ = 7.50 \text{ N} \)

19.18 (a) The magnitude is

\[
F = B I L \sin \theta = (0.60 \times 10^{-4} \text{ T})(15 \text{ A})(10.0 \text{ m}) \sin 90^\circ = 9.0 \times 10^{-3} \text{ N}
\]

\( \vec{F} \) is perpendicular to \( \vec{B} \). Using the right-hand rule number 1, the orientation of \( \vec{F} \) is found to be **15° above the horizontal in the northward direction**.

(b) \( F = B I L \sin \theta = (0.60 \times 10^{-4} \text{ T})(15 \text{ A})(10.0 \text{ m}) \sin 165^\circ = 2.3 \times 10^{-3} \text{ N} \)

and, from the right-hand rule number 1, the direction is **horizontal and due west**.
19.19 For minimum field, \( \mathbf{B} \) should be perpendicular to the wire. If the force is to be northward, the field must be directed \( \text{downward} \).

To keep the wire moving, the magnitude of the magnetic force must equal that of the kinetic friction force. Thus, \( BIL \sin 90^\circ = \mu_k (mg) \), or

\[
B = \frac{\mu_k (m/L)g}{L \sin 90^\circ} = \frac{(0.200)(1.00 \text{ g/cm})(9.80 \text{ m/s}^2)}{(1.50 \text{ A})(1.00)} \left( \frac{1 \text{ kg}}{10^3 \text{ g}} \right) \left( 10^3 \text{ cm} \right) = 0.131 \text{ T}
\]

19.20 To have zero tension in the wires, the magnetic force per unit length must be directed upward and equal to the weight per unit length of the conductor. Thus,

\[
\frac{|\mathbf{F}_m|}{L} = BI = \frac{mg}{L}, \text{ or}
\]

\[
I = \frac{(m/L)g}{B} = \frac{(0.040 \text{ kg/m})(9.80 \text{ m/s}^2)}{3.60 \text{ T}} = 0.109 \text{ A}
\]

From the right-hand rule number 1, the current must be \( \text{to the right} \) if the force is to be upward when the magnetic field is into the page.

19.21 (a) \( \text{The magnetic force must be directed upward and its magnitude must equal } mg \) \( \), the weight of the wire. Then, the net force acting on the wire will be zero and it can move upward at constant speed.

(b) The magnitude of the magnetic force must be \( BIL \sin \theta = mg \), and for minimum field \( \theta = 90^\circ \). Thus,

\[
B_{\text{min}} = \frac{mg}{IL} = \frac{(0.015 \text{ kg})(9.80 \text{ m/s}^2)}{(5.0 \text{ A})(0.15 \text{ m})} = 0.20 \text{ T}
\]

For the magnetic force to be directed upward when the current is toward the left, \( \mathbf{B} \) must be directed \( \text{out of the page} \).

(c) If the field exceeds 0.20 T, the upward magnetic force exceeds the downward force of gravity, so the wire accelerates upward.

19.22 The magnitude of the magnetic force exerted on a current-carrying conductor in a magnetic field is given by \( F = BIL \sin \theta \), where \( B \) is the magnitude of the field, \( L \) is the length of the conductor, \( I \) is the current in the conductor, and \( \theta \) is the angle the conductor makes with the direction of the field. In this case,

\[
F = (0.390 \text{ T})(5.00 \text{ A})(2.80 \text{ m})\sin \theta = (5.46 \text{ N}) \sin \theta
\]

(a) If \( \theta = 60.0^\circ \), then \( \sin \theta = 0.866 \) and \( F = 4.73 \text{ N} \)

(b) If \( \theta = 90.0^\circ \), then \( \sin \theta = 1.00 \) and \( F = 5.46 \text{ N} \)

(c) If \( \theta = 120^\circ \), then \( \sin \theta = 0.866 \) and \( F = 4.73 \text{ N} \)
For each segment, the magnitude of the force is given by \( F = BIL \sin \theta \), and the direction is given by the right-hand rule number 1. The results of applying these to each of the four segments are summarized below.

<table>
<thead>
<tr>
<th>Segment</th>
<th>L (m)</th>
<th>( \theta )</th>
<th>( F ) (N)</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ab )</td>
<td>0.400</td>
<td>180°</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>( bc )</td>
<td>0.400</td>
<td>90.0°</td>
<td>0.040 0</td>
<td>negative ( x )</td>
</tr>
<tr>
<td>( cd )</td>
<td>0.400 ( \sqrt{2} )</td>
<td>45.0°</td>
<td>0.040 0</td>
<td>negative ( z )</td>
</tr>
<tr>
<td>( da )</td>
<td>0.400 ( \sqrt{2} )</td>
<td>90.0°</td>
<td>0.056 6</td>
<td>parallel to ( xz ) plane at 45° to both +( x )- and +( z )-directions</td>
</tr>
</tbody>
</table>

The magnitude of the force is

\[
F = BIL \sin \theta = \left( 5.0 \times 10^{-5} \text{ N} \right) \left( 2.2 \times 10^1 \text{ A} \right) \left( 58 \text{ m} \right) \sin 65° = 5.8 \text{ N}
\]

and the right-hand rule number 1 shows its direction to be into the page.

The torque on a current loop in a magnetic field is \( \tau = BIAN \sin \theta \), and maximum torque occurs when the field is directed parallel to the plane of the loop (\( \theta = 90° \)). Thus,

\[
\tau_{\text{max}} = (0.50 \text{ T}) \left( 25 \times 10^{-3} \text{ A} \right) \left( \pi \left( 5.0 \times 10^{-2} \text{ m} \right)^2 \right) \sin 90° = 4.9 \times 10^{-3} \text{ N} \cdot \text{m}
\]

The magnitude of the torque is \( \tau = NBIA \sin \theta \), where \( \theta \) is the angle between the field and the perpendicular to the plane of the loop. The circumference of the loop is \( 2\pi r = 2.00 \text{ m} \), so the radius is \( r = \frac{1.00 \text{ m}}{\pi} \) and the area is \( A = \pi r^2 = \frac{1}{\pi} \text{ m}^2 \).

Thus,

\[
\tau = (1) \left( 0.800 \text{ T} \right) \left( 17.0 \times 10^{-3} \text{ A} \right) \left( \frac{1}{\pi} \text{ m}^2 \right) \sin 90.0° = 4.33 \times 10^{-3} \text{ N} \cdot \text{m}
\]

The area is \( A = \pi ab = \pi \left( 0.200 \text{ m} \right) \left( 0.150 \text{ m} \right) = 0.0942 \text{ m}^2 \). Since the field is parallel to the plane of the loop, \( \theta = 90.0° \) and the magnitude of the torque is

\[
\tau = NBIA \sin \theta
\]

\[
= 8 \left( 2.00 \times 10^{-4} \text{ T} \right) \left( 6.00 \text{ A} \right) \left( 0.0942 \text{ m}^2 \right) \sin 90.0° = 9.05 \times 10^{-4} \text{ N} \cdot \text{m}
\]

The torque is directed to make the left-hand side of the loop move toward you and the right-hand side move away.

Note that the angle between the field and the perpendicular to the plane of the loop is \( \theta = 90.0° - 30.0° = 60.0° \). Then, the magnitude of the torque is

\[
\tau = NBIA \sin \theta = 100 \left( 0.80 \text{ T} \right) \left( 1.2 \text{ A} \right) \left( 0.40 \text{ m} \right) \left( 0.30 \text{ m} \right) \sin 60.0° = 10 \text{ N} \cdot \text{m}
\]

With current in the \(-\gamma\)-direction, the outside edge of the loop will experience a force directed out of the page (+\( z \)-direction) according to the right-hand rule number 1. Thus, the loop will rotate clockwise as viewed from above.
19.29  (a) The torque exerted on a coil by a uniform magnetic field is $\tau = BIA \sin \theta$, with maximum torque occurring when $\theta = 90^\circ$. Thus, the current in the coil must be

$$I = \frac{\tau_{\text{max}}}{BAN} = \frac{0.15 \, \text{N} \cdot \text{m}}{(0.90 \, \text{T})(3.0 \times 10^{-2} \, \text{m})(5.0 \times 10^{-3} \, \text{m})} = 0.56 \, \text{A}$$

(b) If $I$ has the value found above and $\theta$ is now $25^\circ$, the torque on the coil is

$$\tau = BIA \sin \theta = (0.90 \, \text{T})(0.56 \, \text{A})(0.030 \, \text{m})(0.050 \, \text{m})(200) \sin 25^\circ = 0.064 \, \text{N} \cdot \text{m}$$

19.30  The resistance of the loop is

$$R = \frac{\rho L}{A} = \frac{(1.70 \times 10^{-8} \, \Omega \cdot \text{m})(8.00 \, \text{m})}{1.00 \times 10^{-4} \, \text{m}^2} = 1.36 \times 10^{-3} \, \Omega$$

and the current in the loop is

$$I = \frac{\Delta V}{R} = \frac{0.100 \, \text{V}}{1.36 \times 10^{-3} \, \Omega} = 73.5 \, \text{A}$$

The magnetic field exerts torque $\tau = NBIA \sin \theta$ on the loop, and this is a maximum when $\sin \theta = 1$. Thus,

$$\tau_{\text{max}} = NBIA = (1)(0.400 \, \text{T})(73.5 \, \text{A})(2.00 \, \text{m})^2 = 118 \, \text{N} \cdot \text{m}$$

19.31  (a) Let $\theta$ be the angle the plane of the loop makes with the horizontal as shown in the sketch at the right. Then, the angle it makes with the vertical is $\phi = 90.0^\circ - \theta$. The number of turns on the loop is

$$N = \frac{L}{\text{circumference}} = \frac{4.00 \, \text{m}}{4(0.100 \, \text{m})} = 10.0$$

The torque about the $z$-axis due to gravity is $\tau_z = mg \left(\frac{s}{2} \cos \theta\right)$, where $s = 0.100 \, \text{m}$ is the length of one side of the loop. This torque tends to rotate the loop clockwise. The torque due to the magnetic force tends to rotate the loop counterclockwise about the $z$-axis and has magnitude $\tau_m = NBIA \sin \theta$. At equilibrium, $\tau_m = \tau_z$ or $NBIs \left(\frac{s}{2}\right) \sin \theta = mg \left(\frac{s}{2} \cos \theta\right)$. This reduces to

$$\tan \theta = \frac{mg}{2NBIs} = \frac{(0.100 \, \text{kg})(9.80 \, \text{m/s}^2)}{2(1.00)(0.010 \, \text{T})(3.40 \, \text{A})(0.100 \, \text{m})} = 14.4$$

Since $\tan \theta = \tan (90.0^\circ - \phi) = \cot \phi$, the angle the loop makes with the vertical at equilibrium is $\phi = \cot^{-1}(14.4) = 3.97^\circ$. 

*continued on next page*
b) At equilibrium, 
\[ \tau_\theta = NBI \sin \theta \]
\[ = (10.0)(0.010 \text{ T})(3.40 \text{ A})(0.100 \text{ m})^2 \sin(90.0^\circ - 3.97^\circ) \]
\[ = 3.39 \times 10^{-3} \text{ N} \cdot \text{m} \]

19.32
(a) The current in segment a-b is in the +y-direction. Thus, by right-hand rule 1, the magnetic force on it is in the +x-direction. Imagine this force being concentrated at the center of segment a-b. Then, with a pivot at point a (a point on the x-axis), this force would tend to rotate the conductor a-b in a clockwise direction about the z-axis, so the direction of this torque is in the −z-direction.

(b) The current in segment c-d is in the −y-direction, and the right-hand rule 1 gives the direction of the magnetic force as the −x-direction. With a pivot at point d (a point on the x-axis), this force would tend to rotate the conductor c-d counterclockwise about the z-axis, and the direction of this torque is in the +z-direction.

(c) No. The torques due to these forces are along the z-axis and cannot cause rotation about the x-axis. Further, both the forces and the torques are equal in magnitude and opposite in direction, so they sum to zero and cannot affect the motion of the loop.

(d) The magnetic force is perpendicular to both the direction of the current in b-c (the +x-direction) and the magnetic field. As given by right-hand rule 1, this places it in the yz plane at 130° counterclockwise from the +y-axis. The force acting on segment b-c tends to rotate it counterclockwise about the x-axis, so the torque is in the +x-direction.

(e) The loop tends to rotate counterclockwise about the x-axis.

(f) \[ \mu = IAN = (0.900 \text{ A})[(0.500 \text{ m})(0.300 \text{ m})] = 0.135 \text{ A} \cdot \text{m}^2 \]

(g) The magnetic moment vector is perpendicular to the plane of the loop (the xy plane), and is therefore parallel to the z-axis. Because the current flows clockwise around the loop, the magnetic moment vector is directed downward, in the negative z-direction. This means that the angle between it and the direction of the magnetic field is \( \theta = 90.0^\circ + 40.0^\circ = 130^\circ \).

(h) \[ \tau = \mu B \sin \theta = (0.135 \text{ A} \cdot \text{m}^2)(1.50 \text{ T}) \sin(130^\circ) = 0.155 \text{ N} \cdot \text{m} \]

19.33
(a) The magnetic force acting on the electron provides the centripetal acceleration, holding the electron in the circular path. Therefore, \( F = 1eB \sin 90^\circ = m_e \frac{v^2}{r} \), or
\[ r = \frac{m_e v}{eB} = \frac{(9.11 \times 10^{-31} \text{ kg})(1.5 \times 10^7 \text{ m/s})}{(1.60 \times 10^{-19} \text{ C})(2.0 \times 10^{-3} \text{ T})} = 0.043 \text{ m} = 4.3 \text{ cm} \]

(b) The time to complete one revolution around the orbit (i.e., the period) is
\[ T = \frac{\text{distance traveled}}{\text{constant speed}} = \frac{2\pi r}{\nu} = \frac{2\pi (0.043 \text{ m})}{1.5 \times 10^7 \text{ m/s}} = 1.8 \times 10^{-4} \text{ s} \]
19.34  (a)  \( F = qvB \sin \theta = (1.60 \times 10^{-19} \text{ C})(5.02 \times 10^{6} \text{ m/s})(0.180 \text{ T}) \sin (60.0^\circ) = 1.25 \times 10^{-13} \text{ N} \)

(b)  \( a = \frac{F}{m} = \frac{1.25 \times 10^{-13} \text{ N}}{1.67 \times 10^{-25} \text{ kg}} = 7.50 \times 10^{11} \text{ m/s}^2 \)

19.35  For the particle to pass through with no deflection, the net force acting on it must be zero. Thus, the magnetic force and the electric force must be in opposite directions and have equal magnitudes. This gives

\[ F_c = F_e, \text{ or } qvB = qE, \text{ which reduces to } v = \frac{E}{B} \]

19.36  The speed of the particles emerging from the velocity selector is \( v = \frac{E}{B} \) (see Problem 35).

In the deflection chamber, the magnetic force supplies the centripetal acceleration, so \( qvB = \frac{mv^2}{r} \).

or \( r = \frac{mv}{qB} = \frac{m(\frac{E}{B})}{qB} = \frac{mE}{qB^2} \)

Using the given data, the radius of the path is found to be

\[ r = \frac{(2.18 \times 10^{-26} \text{ kg})(950 \text{ V/m})}{(1.60 \times 10^{-19} \text{ C})(0.930 \text{ T})} = 1.50 \times 10^{-4} \text{ m} = 0.150 \text{ mm} \]

19.37  From conservation of energy, \( (KE + PE)_f = (KE + PE)_i \), we find that \( \frac{1}{2}mv^2 + qV_f = 0 + qV_i \), or the speed of the particle is

\[ v = \sqrt{\frac{2q(V_i - V_f)}{m}} = \sqrt{\frac{2q(\Delta V)}{m}} = \sqrt{\frac{2(1.60 \times 10^{-19} \text{ C})(250 \text{ V})}{2.50 \times 10^{-26} \text{ kg}}} = 5.66 \times 10^4 \text{ m/s} \]

The magnetic force supplies the centripetal acceleration giving \( qvB = \frac{mv^2}{r} \)

or \( r = \frac{mv}{qB} = \frac{(2.50 \times 10^{-26} \text{ kg})(5.66 \times 10^4 \text{ m/s})}{(1.60 \times 10^{-19} \text{ C})(0.500 \text{ T})} = 1.77 \times 10^{-2} \text{ m} = 1.77 \text{ cm} \)

19.38  Since the centripetal acceleration is furnished by the magnetic force acting on the ions, \( qvB = \frac{mv^2}{r} \) or the radius of the path is \( r = \frac{mv}{qB} \). Thus, the distance between the impact points (that is, the difference in the diameters of the paths followed by the U_{238} and the U_{235} isotopes) is

\[ \Delta d = 2(r_{238} - r_{235}) = \frac{2v}{qB}(m_{238} - m_{235}) \]

\[ = \frac{2(3.00 \times 10^4 \text{ m/s})}{(1.60 \times 10^{-19} \text{ C})(0.600 \text{ T})} \left( (238 \text{ u} - 235 \text{ u})\left(1.66 \times 10^{-27} \text{ kg} \text{ u}^{-1}\right) \right) \]

or \( \Delta d = 3.11 \times 10^{-2} \text{ m} = 3.11 \text{ cm} \)
19.39 In the perfectly elastic, head-on collision between the \( \alpha \)-particle and the initially stationary proton, conservation of momentum requires that \( m_p v + m_p v = m_p v \) while conservation of kinetic energy also requires that \( v_0 = 0 \) or \( v = v + v_0 \). Using the fact that \( m_p = 4m_p \) and combining these equations gives

\[
m_p (v + v) + 4m_p v = 4m_p v_0 \quad \text{or} \quad v = 3v_0 / 5
\]

After the collision, each particle follows a circular path in the horizontal plane with the magnetic force supplying the centripetal acceleration. If the radius of the proton’s trajectory is \( R \), we have

\[
q_p v_B = m_p \frac{v^2}{R} \quad \text{or} \quad R = \frac{m_p v}{q_B} = \frac{m_p v}{eB}
\]

A charged particle follows a circular path when it moves perpendicular to the magnetic field. The magnetic force acting on the particle provides the centripetal acceleration, holding the particle in the circular path. Therefore, \( F = qvB \sin 90^\circ = mv^2 / r \). Since the kinetic energy is \( K = mv^2 / 2 \), we rewrite the force as \( F = qvB \sin 90^\circ = 2K / r \) and solving for the speed \( v \) gives

\[
v = \frac{2K}{qBr}
\]

19.40 Within the velocity selector, the electric and magnetic fields exert forces in opposite directions on charged particles passing through. For particles having a particular speed, these forces have equal magnitudes, and the particles pass through without deflection. The selected speed is found from \( F = qE = qvB = F_0 \), giving \( v = E / B \). In the deflection chamber, the selected particles follow a circular path having a diameter of \( d = 2r = 2mv / qB \). Thus, the mass to charge ratio for these particles is

\[
\frac{m}{q} = \frac{Bd}{2v} = \frac{Bd}{2(E / B)} = \frac{(0.0931 \text{ T}) (0.396 \text{ m})}{2(8250 \text{ V/m})} = 2.08 \times 10^{-7} \text{ kg/C}
\]

(b) If the particle is doubly ionized (i.e., two electrons have been removed from the neutral atom), then \( q = 2e \) and the mass of the ion is

\[
m = (2e) \left( \frac{m}{q} \right) = 2 \left( 1.60 \times 10^{-19} \text{ C} \right) \left( 2.08 \times 10^{-7} \text{ kg/C} \right) = 6.66 \times 10^{-26} \text{ kg}
\]

(c) Assuming this is an element, the mass of the ion should be roughly equal to the atomic weight multiplied by the mass of a proton (or neutron). This would give the atomic weight as

\[
\text{At. wt.} = \frac{m}{m_p} = \frac{6.66 \times 10^{-26} \text{ kg}}{1.67 \times 10^{-27} \text{ kg}} = 39.9, \text{ suggesting that the element is calcium.}
\]
19.42 Since the path is circular, the particle moves perpendicular to the magnetic field, and the magnetic force supplies the centripetal acceleration. Hence, \( \frac{mv^2}{r} = qvB \), or \( B = \frac{mv}{qr} \). But the momentum is given by \( p = mv = \sqrt{2m(KE)} \), and the kinetic energy of this proton is

\[
KE = (10.0 \times 10^6 \text{ eV}) \left( \frac{1.60 \times 10^{-19} \text{ J}}{1 \text{ eV}} \right) = 1.60 \times 10^{-12} \text{ J}
\]

We then have

\[
B = \frac{\sqrt{2m(KE)}}{q} = \sqrt{\left(2 \times 1.67 \times 10^{-27} \text{ kg}\right)\left(1.60 \times 10^{-12} \text{ J}\right)} = \left( \frac{1.60 \times 10^{-10} \text{ C}}{5.80 \times 10^3 \text{ m}} \right) = 7.88 \times 10^{-12} \text{ T}
\]

19.43 Treat the lightning bolt as a long, straight conductor. Then, the magnetic field is

\[
B = \frac{\mu_0 I}{2\pi r} = \left( \frac{4\pi \times 10^{-7} \text{ T} \cdot \text{m/A}}{2\pi (100 \text{ m})} \right) = 2.00 \times 10^{-7} \text{ T} = 20. \mu\text{T}
\]

19.44 Imagine grasping the conductor with the right hand so the fingers curl around the conductor in the direction of the magnetic field. The thumb then points along the conductor in the direction of the current. The results are

(a) toward the left (b) out of page (c) lower left to upper right

19.45 The magnetic field at distance \( r \) from a long conducting wire is \( B = \frac{\mu_0 I}{2\pi r} \). Thus, if \( B = 1.0 \times 10^{-15} \text{ T} \) at \( r = 4.0 \text{ cm} \), the current must be

\[
I = \frac{2\pi r B}{\mu_0} = \frac{2\pi (0.040 \text{ m})(1.0 \times 10^{-15} \text{ T})}{4\pi \times 10^{-7} \text{ T} \cdot \text{m/A}} = 2.0 \times 10^{-10} \text{ A}
\]

19.46 Model the tornado as a long, straight, vertical conductor and imagine grasping it with the right hand so the fingers point northward on the western side of the tornado (that is, at the observatory’s location). The thumb is directed downward, meaning that the conventional current is downward or negative charge flows upward.

The magnitude of the current is found from \( B = \frac{\mu_0 I}{2\pi r} \) as

\[
I = \frac{2\pi r B}{\mu_0} = \frac{2\pi (9.00 \times 10^3 \text{ m})(1.50 \times 10^{-8} \text{ T})}{4\pi \times 10^{-7} \text{ T} \cdot \text{m/A}} = 675 \text{ A}
\]

19.47 From \( B = \frac{\mu_0 I}{2\pi r} \), the required distance is

\[
r = \frac{\mu_0 I}{2\pi B} \left( \frac{4\pi \times 10^{-7} \text{ T} \cdot \text{m/A}}{2\pi (1.7 \times 10^{-3} \text{ T})} \right) = 2.4 \times 10^{-3} \text{ m} = 2.4 \text{ mm}
\]
Assume that the wire on the right is wire 1 and that on the left is wire 2. Also, choose the positive direction for the magnetic field to be out of the page and negative into the page.

(a) At the point half way between the two wires,

\[ B_{\text{net}} = -B_1 - B_2 = -\left(\frac{\mu_0 I_1}{2\pi r_1} + \frac{\mu_0 I_2}{2\pi r_2}\right) = -\frac{\mu_0}{2\pi r} (I_1 + I_2) \]

\[ = -\left(\frac{4\pi \times 10^{-7} \text{ T} \cdot \text{m/A}}{2\pi (5.00 \times 10^{-2} \text{ m})}\right) (10.0 \text{ A}) = -4.00 \times 10^{-5} \text{ T} \]

or \( B_{\text{net}} = 40.0 \mu\text{T into the page} \)

(b) At point \( P_1 \),

\[ B_{\text{net}} = +B_1 - B_2 = \frac{\mu_0}{2\pi} \left[ \frac{I_1}{r_1} - \frac{I_2}{r_2} \right] \]

\[ B_{\text{net}} = \frac{4\pi \times 10^{-7} \text{ T} \cdot \text{m/A}}{2\pi} \left[ \frac{5.00 \text{ A}}{0.100 \text{ m}} - \frac{5.00 \text{ A}}{0.200 \text{ m}} \right] = 5.00 \mu\text{T out of page} \]

(c) At point \( P_2 \),

\[ B_{\text{net}} = -B_1 + B_2 = -\frac{\mu_0}{2\pi} \left[ \frac{I_1}{r_1} + \frac{I_2}{r_2} \right] \]

\[ B_{\text{net}} = \frac{4\pi \times 10^{-7} \text{ T} \cdot \text{m/A}}{2\pi} \left[ -\frac{5.00 \text{ A}}{0.300 \text{ m}} + \frac{5.00 \text{ A}}{0.200 \text{ m}} \right] = 1.67 \mu\text{T out of page} \]

19.49 The distance from each wire to point \( P \) is given by

\[ r = \frac{1}{2} \sqrt{(0.200 \text{ m})^2 + (0.200 \text{ m})^2} = 0.141 \text{ m} \]

At point \( P \), the magnitude of the magnetic field produced by each of the wires is

\[ B = \frac{\mu_0 I}{2\pi r} = \frac{4\pi \times 10^{-7} \text{ T} \cdot \text{m/A}}{2\pi (0.141 \text{ m})} = 7.07 \mu\text{T} \]

Carrying currents into the page, the field \( A \) produces an upward and to the left field at \(-135^\circ\), while \( B \) creates a field to the right and down at \(-45^\circ\). Carrying currents toward you, \( C \) produces a field downward and to the right at \(-45^\circ\), while \( D \)'s contribution is down and to the left at \(-135^\circ\). The horizontal components of these equal magnitude contributions cancel in pairs, while the vertical components all add. The total field is then

\[ B_{\text{net}} = 4(7.07 \mu\text{T}) \sin 45.0^\circ = 20.0 \mu\text{T toward the bottom of the page} \]
19.50 Call the wire carrying a current of 3.00 A wire 1 and the other wire 2. Also, choose the line running from wire 1 to wire 2 as the positive $x$-direction.

(a) At the point midway between the wires, the field due to each wire is parallel to the $y$-axis and the net field is

$$B_{\text{net}} = B_{y_1} - B_{y_2} = \frac{\mu_0 (I_1 - I_2)}{2\pi r}$$

Thus,

$$B_{\text{net}} = \frac{4\pi \times 10^{-7} \ T \cdot \text{m/A}}{2\pi (0.100 \ \text{m})} (3.00 \ \text{A} - 5.00 \ \text{A}) = -4.00 \times 10^{-6} \ \text{T}$$

or

$$B_{\text{net}} = \boxed{-4.00 \ \mu T \ \text{toward the bottom of the page}}$$

(b) At point $P$, $r_i = (0.200 \ \text{m})\sqrt{2}$ and $B_i$ is directed at $\theta_i = +135^\circ$.

The magnitude of $B_i$ is

$$B_i = \frac{\mu_0 I_i}{2\pi r_i} = \frac{4\pi \times 10^{-7} \ \text{T} \cdot \text{m/A}}{2\pi (0.200 \ \sqrt{2} \ \text{m})} = 2.12 \ \mu \text{T}$$

The contribution from wire 2 is in the $-x$-direction and has magnitude

$$B_2 = \frac{\mu_0 I_2}{2\pi r_2} = \frac{4\pi \times 10^{-7} \ \text{T} \cdot \text{m/A}}{2\pi (0.200 \ \text{m})} = 5.00 \ \mu \text{T}$$

Therefore, the components of the net field at point $P$ are:

$$B_x = B_i \cos 135^\circ + B_2 \cos 180^\circ$$

$$= (2.12 \ \mu \text{T}) \cos 135^\circ + (5.00 \ \mu \text{T}) \cos 180^\circ = -6.50 \ \mu \text{T}$$

and

$$B_y = B_i \sin 135^\circ + B_2 \sin 180^\circ = (2.12 \ \mu \text{T}) \sin 135^\circ + 0 = +1.50 \ \mu \text{T}$$

Therefore,

$$B_{\text{net}} = \sqrt{B_x^2 + B_y^2} = 6.67 \ \mu \text{T} \ \text{at}$$

$$\theta = \tan^{-1} \left( \frac{B_y}{B_x} \right) = \tan^{-1} \left( \frac{1.50 \ \mu \text{T}}{6.50 \ \mu \text{T}} \right) = 17.7^\circ$$

or

$$\boxed{B_{\text{net}} = 6.67 \ \mu \text{T} \ \text{at} \ 17.7^\circ \ \text{to the left of vertical}}$$

19.51 Call the wire along the $x$-axis wire 1 and the other wire 2. Also, choose the positive direction for the magnetic fields at point $P$ to be out of the page.

At point $P$, $B_{\text{net}} = +B_i - B_2 = \frac{\mu_0 I_1}{2\pi r_1} - \frac{\mu_0 I_2}{2\pi r_2} = \frac{\mu_0}{2\pi} \left( \frac{I_1}{r_1} - \frac{I_2}{r_2} \right)$

or

$$B_{\text{net}} = \frac{4\pi \times 10^{-7} \ \text{T} \cdot \text{m/A}}{2\pi} \left( \frac{7.00 \ \text{A}}{3.00 \ \text{m}} - \frac{6.00 \ \text{A}}{4.00 \ \text{m}} \right) = +1.67 \times 10^{-5} \ \text{T}$$

$$B_{\text{net}} = \boxed{0.167 \ \mu \text{T} \ \text{out of the page}}$$
19.52 (a) Imagine the horizontal xy plane being perpendicular to the page, with the positive x-axis coming out of the page toward you and the positive y-axis toward the right edge of the page. Then, the vertically upward positive z-axis is directed toward the top of the page. With the current in the wire flowing in the positive x-direction, the right-hand rule 2 gives the direction of the magnetic field above the wire as being toward the left, or in the −y-direction.

(b) With the positively charged proton moving in the −x-direction (into the page), right-hand rule 1 gives the direction of the magnetic force on the proton as being directed toward the top of the page, or upward, in the positive z-direction.

(c) Since the proton moves with constant velocity, a zero net force acts on it. Thus, the magnitude of the magnetic force must equal that of the gravitational force.

(d) \( \Sigma F_x = ma_x = 0 \Rightarrow F_x = F_y \) or \( qvB = mg \) where \( B = \mu_0 I / 2\pi d \). This gives \( qv\mu_0 I = mg \), or the distance the proton is above the wire must be \( d = \frac{qv\mu_0 I}{2\pi mg} \).

(e) \( d = \frac{qv\mu_0 I}{2\pi mg} = \left( \frac{1.60 \times 10^{-19} \text{ C}}{2.30 \times 10^4 \text{ m/s}} \right) \left( 4\pi \times 10^{-7} \text{ T m/A} \right) \left( 1.20 \times 10^{-6} \text{ A} \right) \times \left( \frac{2\pi}{1.67 \times 10^{-27} \text{ kg}} \right) \left( 9.80 \text{ m/s}^2 \right) \)
\[ d = 5.40 \times 10^{-2} \text{ m} = 5.40 \text{ cm} \]

19.53 (a) From \( B = \mu_0 I / 2\pi r \), observe that the field is inversely proportional to the distance from the conductor. Thus, the field will have one-tenth its original value if the distance is increased by a factor of 10. The required distance is then \( r' = 10r = 10(0.400 \text{ m}) = 4.00 \text{ m} \).

(b) A point in the plane of the conductors and 40.0 cm from the center of the cord is located 39.85 cm from the nearer wire and 40.15 cm from the far wire. Since the currents are in opposite directions, so are their contributions to the net field. Therefore, \( B_{net} = B_1 - B_2 \), or

\[ B_{net} = \frac{\mu_0 I}{2\pi} \left( \frac{1}{r_1} - \frac{1}{r_2} \right) = \frac{\mu_0 I}{2\pi} \left( \frac{1}{0.3985 \text{ m}} - \frac{1}{0.4015 \text{ m}} \right) \]
\[ = 7.50 \times 10^{-9} \text{ T} = 7.50 \text{ nT} \]

(c) Call \( r \) the distance from cord center to field point \( P \) and \( 2d = 3.00 \text{ mm} \) the distance between centers of the conductors.

\[ B_{net} = \frac{\mu_0 I}{2\pi} \left( \frac{1}{r - d} - \frac{1}{r + d} \right) = \frac{\mu_0 I}{2\pi} \left( \frac{2d}{r^2 - d^2} \right) \]
\[ 7.50 \times 10^{-9} \text{ T} = \frac{\left( 4\pi \times 10^{-7} \text{ T m/A} \right) \left( 2.00 \text{ A} \right) \left( 3.00 \times 10^{-3} \text{ m} \right)}{2\pi \left( r^2 - 2.25 \times 10^{-6} \text{ m}^2 \right)} \]
so \( r = 1.26 \text{ m} \)

The field of the two-conductor cord is weak to start with and falls off rapidly with distance.

(d) The cable creates zero field at exterior points, since a loop in Ampère’s law encloses zero total current.
19.54 (a) Point \( P \) is equidistant from the two wires, which carry identical currents. Thus, the contributions of the two wires, \( \mathbf{B}_{\text{upper}} \) and \( \mathbf{B}_{\text{lower}} \), to the magnetic field at \( P \) will have equal magnitudes. The horizontal components of these contributions will cancel, while the vertical components add. The resultant field will be vertical, in the \( +y \)-direction.

(b) The distance of each wire from point \( P \) is \( r = \sqrt{x^2 + d^2} \), and the cosine of the angle that \( \mathbf{B}_{\text{upper}} \) and \( \mathbf{B}_{\text{lower}} \) make with the vertical is \( \cos \theta = x/r \). The magnitude of either \( \mathbf{B}_{\text{upper}} \) or \( \mathbf{B}_{\text{lower}} \) is \( B_{\text{wire}} = \mu_0 I/2\pi r \) and the vertical components of either of these contributions have values of

\[
(B_{\text{wire}})_y = (B_{\text{wire}}) \cos \theta = \left( \frac{\mu_0 I}{2\pi r} \right) \frac{x}{r} = \frac{\mu_0 I x}{2\pi r^2}
\]

The magnitude of the resultant field at point \( P \) is then

\[
B_y = 2(B_{\text{wire}})_y = \frac{\mu_0 I x}{\pi (x^2 + d^2)}
\]

(c) The point midway between the two wires is the origin \((0,0)\). From the above result for part (b), the resultant field at this midpoint is \( B_y|_{0,0} = 0 \). This is as expected, because right-hand rule 2 shows that at the midpoint the field due to the upper wire is toward the right, while that due to the lower wire is toward the left. Thus, the two fields cancel, yielding a zero resultant field.

19.55 The force per unit length that one wire exerts on the other is \( F/\ell = \mu_0 I I_z/2\pi d \), where \( d \) is the distance separating the two wires. In this case, the value of this force is

\[
F = \frac{\mu_0 I I_z}{2\pi d} = \frac{\left[ 4\pi \times 10^{-7}\ T \cdot m/A \right] \times [3.0\ A]^2}{2\pi (6.00 \times 10^{-3}\ m)} = 3.0 \times 10^{-5}\ N/m
\]

Imagine these two wires lying side by side on a table with the two currents flowing toward you, wire 1 on the left and wire 2 on the right. Right-hand rule 2 shows the magnetic field due to wire 1 at the location of wire 2 is directed vertically upward. Then, right-hand rule 1 gives the direction of the force experienced by wire 2, with its current flowing through this field, as being to the left, back toward wire 1. Thus, the force one wire exerts on the other is an attractive force.

19.56 (a) The force per unit length that parallel conductors exert on each other is \( F/\ell = \mu_0 I I_z/2\pi d \). Thus, if \( F/\ell = 2.0 \times 10^{-4}\ N/m \), \( I_z = 5.0\ A \), and \( d = 4.0\ cm \), the current in the second wire must be

\[
I_z = \frac{2\pi d F}{\mu_0 I\ell} = \frac{2\pi \left( 4.0 \times 10^{-2}\ m \right)}{\left( 4\pi \times 10^{-7}\ T \cdot m/A \right) \times [5.0\ A]} \left( 2.0 \times 10^{-4}\ N/m \right) = 8.0\ A
\]

(b) Since parallel conductors carrying currents in the same direction attract each other (see Section 19.8 in the textbook), the currents in these conductors which repel each other must be in opposite directions.

continued on next page
(c) The result of reversing the direction of either of the currents would be that the force of interaction would change from a force of repulsion to an attractive force. The expression for the force per unit length, \( F/\ell = \mu_0 I_1 I_2 / (2\pi d) \), shows that doubling either of the currents would double the magnitude of the force of interaction.

19.57 In order for the system to be in equilibrium, the repulsive magnetic force per unit length on the top wire must equal the weight per unit length of this wire.

Thus, \( F_\ell = \mu_0 I_1 I_2 / (2\pi d) = 0.080 \) N/m, and the distance between the wires will be

\[
d = \frac{\mu_0 I_1 I_2}{2\pi (0.080 \text{ N/m})} = \frac{(4\pi \times 10^{-7} \text{ T m/A})(60.0 \text{ A})(30.0 \text{ A})}{2\pi (0.080 \text{ N/m})}
\]

\[
d = 4.5 \times 10^{-3} \text{ m} = 4.5 \text{ mm}
\]

19.58 The magnetic forces exerted on the top and bottom segments of the rectangular loop are equal in magnitude and opposite in direction. Thus, these forces cancel, and we only need consider the sum of the forces exerted on the right and left sides of the loop. Choosing to the left (toward the long, straight wire) as the positive direction, the sum of these two forces is

\[
F_{\text{net}} = \frac{\mu_0 I_1 I_2 \ell}{2\pi c} - \frac{\mu_0 I_1 I_2 \ell}{2\pi (c + a)} = \frac{\mu_0 I_1 I_2 \ell}{2\pi} \left( \frac{1}{c} - \frac{1}{c + a} \right)
\]

or

\[
F_{\text{net}} = \frac{(4\pi \times 10^{-7} \text{ T m/A})(5.00 \text{ A})(10.0 \text{ A})(0.450 \text{ m})}{2\pi} \left( \frac{1}{0.100 \text{ m}} - \frac{1}{0.250 \text{ m}} \right)
\]

\[
F_{\text{net}} = +2.70 \times 10^{-5} \text{ N} \quad \text{to the left}
\]

19.59 The magnetic field inside of a solenoid is \( B = \mu_0 n I = \mu_0 (N/L)I \). Thus, the current in this solenoid must be

\[
I = \frac{BL}{\mu_0 N} = \frac{(2.0 \times 10^{-3} \text{ T})(6.0 \times 10^{-3} \text{ m})}{(4\pi \times 10^{-7} \text{ T m/A})(30)} = 3.2 \text{ A}
\]

19.60 The magnetic field inside of a solenoid is \( B = \mu_0 n I = \mu_0 (N/L)I \). Thus, the number of turns on this solenoid must be

\[
N = \frac{BL}{\mu_0 I} = \frac{(9.0 \text{ T})(0.50 \text{ m})}{(4\pi \times 10^{-7} \text{ T m/A})(75 \text{ A})} = 4.8 \times 10^4 \text{ turns}
\]
19.61 (a) From $R = \rho L/A$, the required length of wire to be used is

$$L = \frac{R \cdot A}{\rho} = \frac{(5.00 \, \Omega) \left[ \pi \left(0.500 \times 10^{-3} \, \text{m}\right)^2 / 4 \right]}{1.7 \times 10^4 \, \Omega \cdot \text{m}} = 58 \, \text{m}$$

The total number of turns on the solenoid (that is, the number of times this length of wire will go around a 1.00 cm radius cylinder) is

$$N = \frac{L}{2\pi r} = \frac{58 \, \text{m}}{2\pi(1.00 \times 10^{-2} \, \text{m})} = 9.2 \times 10^2 = 920$$

(b) From $B = \mu_0 n I$, the number of turns per unit length on the solenoid is

$$n = \frac{B}{\mu_0 n I} = \frac{4.00 \times 10^{-7} \, \text{T}}{(4\pi \times 10^{-7} \, \text{T} \cdot \text{m/A})(4.00 \, \text{A})} = 7.96 \times 10^3 \, \text{turns/m}$$

Thus, the required length of the solenoid is

$$L = \frac{N}{n} = \frac{9.2 \times 10^2 \, \text{turns}}{7.96 \times 10^3 \, \text{turns/m}} = 0.12 \, \text{m} = 12 \, \text{cm}$$

19.62 The magnetic field inside the solenoid is

$$B = \mu_0 n I = (4\pi \times 10^{-7} \, \text{T} \cdot \text{m/A}) \left[ \left(30 \, \text{turns/cm} \right) \left( \frac{100 \, \text{cm}}{1 \, \text{m}} \right) \right] (15.0 \, \text{A}) = 5.65 \times 10^{-2} \, \text{T}$$

Therefore, the magnitude of the magnetic force on any one of the sides of the square loop is

$$F = BI \sin 90.0^\circ = (5.65 \times 10^{-2} \, \text{T})(0.200 \, \text{A})(2.00 \times 10^{-2} \, \text{m}) = 2.26 \times 10^{-5} \, \text{N}$$

The forces acting on the sides of the loop lie in the plane of the loop, are perpendicular to the sides, and are directed away from the interior of the loop. Thus, they tend to stretch the loop but do not tend to rotate it. The torque acting on the loop is $\tau = 0$.

19.63 (a) The magnetic force supplies the centripetal acceleration, so $qvB = m v^2/r$. The magnetic field inside the solenoid is then found to be

$$B = \frac{mv}{qr} = \frac{(9.11 \times 10^{-31} \, \text{kg})(1.0 \times 10^4 \, \text{m/s})}{(1.60 \times 10^{-19} \, \text{C})(2.0 \times 10^{-3} \, \text{m})} = 2.8 \times 10^{-6} \, \text{T} = 2.8 \, \mu\text{T}$$

(b) From $B = \mu_0 n I$, the current is the solenoid is found to be

$$I = \frac{B}{\mu_0 n} = \frac{2.8 \times 10^{-6} \, \text{T}}{(4\pi \times 10^{-7} \, \text{T} \cdot \text{m/A})(25 \, \text{turns/cm})(100 \, \text{cm}/1 \, \text{m})} = 8.9 \times 10^{-4} \, \text{A} = 0.89 \, \text{mA}$$
19.64 (a) When switch $S$ is closed, a total current $NI$ (current $I$ in a total of $N$ conductors) flows toward the right through the lower side of the coil. This results in a downward force of magnitude $F_m = B(NI)w$ being exerted on the coil by the magnetic field, with the requirement that the balance exert an upward force $F' = mg$ on the coil to bring the system back into balance.

In order for the magnetic force to be downward, the right-hand rule number 1 shows that the magnetic field must be directed out of the page toward the reader. For the system to be restored to balance, it is necessary that

$$F_m = F' \quad \text{or} \quad B(NI)w = mg, \text{ giving } B = \frac{mg}{Nh\mu}$$

(b) The magnetic field exerts forces of equal magnitudes and opposite directions on the two sides of the coil. These forces cancel each other and do not affect the balance of the coil. Hence the dimension of the sizes is not needed.

(c) $B = \frac{mg}{Nh\mu} = \frac{(20.0 \times 10^{-3} \text{ kg})(9.80 \text{ m/s}^2)}{(50)(0.30 \text{ A})(5.0 \times 10^{-2} \text{ m})} = 0.26 \text{ T}$

19.65 (a) The magnetic field at the center of a circular current loop of radius $R$ and carrying current $I$ is $B = \mu_0 I/2R$. The direction of the field at this center is given by right-hand rule number 2. Taking out of the page (toward the reader) as positive the net magnetic field at the common center of these coplanar loops is

$$B_{\text{net}} = B_2 - B_1 = \frac{\mu_0 I_2}{2r_2} - \frac{\mu_0 I_1}{2r_1} = \frac{\left(4\pi \times 10^{-7} \text{ T} \cdot \text{m/A}\right)}{2} \left(\frac{3.0 \text{ A}}{9.0 \times 10^{-2} \text{ m}} - \frac{5.0 \text{ A}}{12 \times 10^{-2} \text{ m}}\right)$$

$$= -5.2 \times 10^{-8} \text{ T} = 5.2 \mu\text{T into the page}$$

(b) To have $B_{\text{net}} = 0$, it is necessary that $I_2/r_2 = I_1/r_1$, or

$$r_2 = \left(\frac{I_2}{I_1}\right) r_1 = \left(\frac{3.0 \text{ A}}{5.0 \text{ A}}\right) (12 \text{ cm}) = 7.2 \text{ cm}$$

19.66 Since the magnetic force must supply the centripetal acceleration, $qBv = m v^2/r$ or the radius of the path is $r = mv/qB$.

(a) The time for the electron to travel the semicircular path (of length $\pi r$) is

$$t = \frac{\pi r}{v} = \frac{\pi}{v} \left(\frac{mv}{qB}\right) = \frac{\pi m}{qB} = \frac{\pi \left(9.11 \times 10^{-31} \text{ kg}\right)}{(1.60 \times 10^{-19} \text{ C})(0.0100 \text{ T})}$$

$$= 1.79 \times 10^{-8} \text{ s} = 1.79 \text{ ns}$$

continued on next page
(b) The radius of the semicircular path is 2.00 cm. From \( r = \frac{mv}{qB} \), the momentum of the electron is \( p = mv = qBr \), and the kinetic energy is

\[
KE = \frac{1}{2}mv^2 = \frac{(mv)^2}{2m} = \frac{q^2B^2r^2}{2m} = \frac{(1.60 \times 10^{-19} \text{ C})^2 (0.0100 \text{ T})^2 (2.00 \times 10^{-2} \text{ m})^2}{2 (9.11 \times 10^{-31} \text{ kg})}
\]

\[
KE = \left( 5.62 \times 10^{-16} \text{ J} \right) \left( \frac{1 \text{ keV}}{1.60 \times 10^{-16} \text{ J}} \right) = 3.51 \text{ keV}
\]

19.67 Assume wire 1 is along the \( x \)-axis and wire 2 along the \( y \)-axis.

(a) Choosing out of the page as the positive field direction, the field at point \( P \) is

\[
B = B_1 - B_2 = \frac{\mu_0 (I_1 - I_2)}{2\pi (r_1 - r_2)} = \frac{4\pi \times 10^{-7} \text{ T} \cdot \text{m/A}}{2\pi} \left( \frac{5.00 \text{ A}}{0.400 \text{ m}} - \frac{3.00 \text{ A}}{0.300 \text{ m}} \right)
\]

\[
= 5.00 \times 10^{-2} \text{ T} = 0.500 \mu \text{T out of the page}
\]

(b) At 30.0 cm above the intersection of the wires, the field components are as shown at the right, where

\[
B_y = -B_1 = -\frac{\mu_0 I_1}{2\pi r} = -\frac{(4\pi \times 10^{-7} \text{ T} \cdot \text{m/A})(5.00 \text{ A})}{2\pi (0.300 \text{ m})} = -3.33 \times 10^{-6} \text{ T}
\]

and \( B_x = B_2 = \frac{\mu_0 I_2}{2\pi r} = \frac{(4\pi \times 10^{-7} \text{ T} \cdot \text{m/A})(3.00 \text{ A})}{2\pi (0.300 \text{ m})} = 2.00 \times 10^{-6} \text{ T} \)

The resultant field is

\[
B = \sqrt{B_x^2 + B_y^2} = 3.89 \times 10^{-6} \text{ T} \text{ at } \theta = \tan^{-1} \left( \frac{B_y}{B_x} \right) = -59.0^\circ
\]

or \( B = 3.89 \mu \text{T at } 59.0^\circ \) clockwise from \( +x \) direction
19.68 For the rail to move at constant velocity, the net force acting on it must be zero. Thus, the magnitude of the magnetic force must equal that of the friction force giving $BIL = \mu_m (mg)$, or

$$B = \frac{\mu_m (mg)}{IL} = \frac{(0.100)(0.200 \text{ kg})(9.80 \text{ m/s}^2)}{(10.0 \text{ A})(0.500 \text{ m})} = 3.92 \times 10^{-2} \text{ T}$$

19.69 (a) Since the magnetic field is directed from N to S (that is, from left to right within the artery), positive ions with velocity in the direction of the blood flow experience a magnetic deflection toward electrode $A$. Negative ions will experience a force deflecting them toward electrode $B$. This separation of charges creates an electric field directed from $A$ toward $B$. At equilibrium, the electric force caused by this field must balance the magnetic force, so

$$qeB = qE = q\left(\frac{\Delta V}{d}\right)$$

or

$$v = \frac{\Delta V}{Bd} = \frac{160 \times 10^{-6} \text{ V}}{(0.0400 \text{ T})(3.00 \times 10^{-3} \text{ m})} = 1.33 \text{ m/s}$$

(b) The magnetic field is directed from N to S. If the charge carriers are negative moving in the direction of $\vec{v}$, the magnetic force is directed toward point $B$. Negative charges build up at point $B$, making the potential at $A$ higher than that at $B$. If the charge carriers are positive moving in the direction of $\vec{v}$, the magnetic force is directed toward $A$, so positive charges build up at $A$. This also makes the potential at $A$ higher than that at $B$. Therefore, the sign of the potential difference does not depend on the charge of the ions.

19.70 (a) The magnetic force acting on the wire is directed upward and of magnitude

$$F_m = BIL \sin 90^\circ = BIL$$

Thus, $a_x = \frac{\sum F_x}{m} = \frac{F_m - mg}{m} = \frac{BI}{mL} - g$, or

$$a_x = \frac{(4.0 \times 10^{-3} \text{ T})(2.0 \text{ A})}{5.0 \times 10^{-3} \text{ kg/m}} - 9.80 \text{ m/s}^2 = 6.2 \text{ m/s}^2$$

(b) Using $\Delta y = v_{0y} t + \frac{1}{2} a_y t^2$ with $v_{0y} = 0$ gives

$$t = \sqrt{\frac{2(\Delta y)}{a_y}} = \sqrt{\frac{2(0.50 \text{ m})}{6.2 \text{ m/s}^2}} = 0.40 \text{ s}$$
Label the wires 1, 2, and 3 as shown in Figure 1, and let $B_1$, $B_2$, and $B_3$ respectively represent the magnitudes of the fields produced by the currents in those wires. Also, observe that $\theta = 45^\circ$ in Figure 1.

At point $A$, $B_1 = B_2 = \frac{\mu_0 I}{2\pi a} = \frac{(4\pi \times 10^{-7} \text{ T} \cdot \text{m/A})(2.0 \text{ A})}{2\pi(0.010 \text{ m})} = 28 \mu \text{T}$

and $B_3 = \frac{\mu_0 I}{2\pi(3a)} = \frac{(4\pi \times 10^{-7} \text{ T} \cdot \text{m/A})(2.0 \text{ A})}{2\pi(0.030 \text{ m})} = 13 \mu \text{T}$

These field contributions are oriented as shown in Figure 2. Observe that the horizontal components of $B_1$ and $B_3$ cancel while their vertical components add to $B_2$. The resultant field at point $A$ is then

$$B_a = (B_1 + B_2) \cos 45^\circ + B_3 = 53 \mu \text{T},$$

or

$$B_a = \begin{array}{c} 53 \mu \text{T} \text{ directed toward the bottom of the page} \end{array}$$

At point $B$, $B_1 = \frac{\mu_0 I}{2\pi a} = \frac{(4\pi \times 10^{-7} \text{ T} \cdot \text{m/A})(2.0 \text{ A})}{2\pi(0.010 \text{ m})} = 40 \mu \text{T}$

and $B_3 = \frac{\mu_0 I}{2\pi(2a)} = 20 \mu \text{T}$. These contributions are oriented as shown in Figure 3. Thus, the resultant field at $B$ is

$$B_a = B_3 = \begin{array}{c} 20 \mu \text{T} \text{ directed toward the bottom of the page} \end{array}$$

At point $C$, $B_1 = B_3 = \frac{\mu_0 I}{2\pi a} = 28 \mu \text{T}$ while $B_2 = \frac{\mu_0 I}{2\pi a} = 40 \mu \text{T}$. These contributions are oriented as shown in Figure 4. Observe that the horizontal components of $B_1$ and $B_3$ cancel while their vertical components add to oppose $B_2$. The magnitude of the resultant field at $C$ is

$$B_c = (B_1 + B_3) \sin 45^\circ - B_2$$

$$= (56 \mu \text{T}) \sin 45^\circ - 40 \mu \text{T} = 0$$
19.72 (a) Since one wire repels the other, the currents must be in opposite directions.

(b) Consider a free body diagram of one of the wires as shown at the right.

\[ \sum F_i = 0 \Rightarrow T \cos 8.0^\circ = mg \]

or

\[ T = \frac{mg}{\cos 8.0^\circ} \]

\[ \sum F_i = 0 \Rightarrow F_m = T \sin 8.0^\circ = \left( \frac{mg}{\cos 8.0^\circ} \right) \sin 8.0^\circ \]

or

\[ F_m = (mg) \tan 8.0^\circ. \] Thus, \( \frac{\mu_0 I^2 L}{2\pi d} = (mg) \tan 8.0^\circ \) which gives

\[ I = \sqrt{\frac{\mu_0 I^2 L}{2\pi d}} \tan 8.0^\circ \]

Observe that the distance between the two wires is

\[ d = 2 \left( 6.0 \text{ cm} \sin 8.0^\circ \right) = 1.7 \text{ cm}, \] so

\[ I = \sqrt{\frac{1.7 \times 10^{-2} \text{ m}}{2.0 \times 10^{-7} \text{ T} \cdot \text{m/A}}} \tan 8.0^\circ = 68 \text{ A} \]

19.73 Note: We solve part (b) before part (a) for this problem.

(b) Since the magnetic force supplies the centripetal acceleration for this particle, \( qvB = mv^2/r \)

or the radius of the path is \( r = mt/qB \). The speed of the particle may be written as

\[ v = \sqrt{2(KE)/m}, \] so the radius becomes

\[ r = \sqrt{\frac{2m(KE)}{qB}} = \sqrt{\frac{2(1.67 \times 10^{-27} \text{ kg})(5.00 \times 10^4 \text{ eV})[1.60 \times 10^{-19} \text{ J/eV}]}{(1.60 \times 10^{-19} \text{ C})(0.050 \text{ T})}} = 6.46 \text{ m} \]

Consider the circular path shown at the right and observe that the desired angle is

\[ \alpha = \sin^{-1} \left( \frac{1.00 \text{ m}}{r} \right) = \sin^{-1} \left( \frac{1.00 \text{ m}}{6.46 \text{ m}} \right) = 89.0^\circ \]

continued on next page
(a) The constant speed of the particle is \( v = \sqrt{2(KE)/m} \), so the vertical component of the momentum as the particle leaves the field is

\[
p_y = m v_y = -m v \sin \alpha = -m \left( \sqrt{2(KE)/m} \right) \sin \alpha = -\sin \alpha \sqrt{2mKE}
\]

or

\[
p_y = -\sin(8.90^\circ) \sqrt{2 \times 1.67 \times 10^{-37} \text{ kg} \times (5.00 \times 10^6 \text{ eV}) \times (1.60 \times 10^{-19} \text{ J/eV})}
\]

\[
= -8.00 \times 10^{-21} \text{ kg} \cdot \text{m/s}
\]

19.74 The force constant of the spring system is found from the elongation produced by the weight acting alone.

\[
k = \frac{F_x}{x} = \frac{mg}{x} = \frac{10.0 \times 10^{-3} \text{ kg} \times (9.80 \text{ m/s}^2)}{0.50 \times 10^{-2} \text{ m}} = 19.6 \text{ N/m}
\]

The total force stretching the springs when the field is turned on is

\[
\Sigma F_y = F_m + mg = kx_{\text{total}}
\]

Thus, the downward magnetic force acting on the wire is

\[
F_m = kx_{\text{total}} - mg
\]

\[
= (19.6 \text{ N/m}) (0.80 \times 10^{-2} \text{ m}) - (10.0 \times 10^{-3} \text{ kg}) (9.80 \text{ m/s}^2)
\]

\[
= 5.9 \times 10^{-2} \text{ N}
\]

Since the magnetic force is given by \( F_m = BIL \sin 90^\circ \), the magnetic field is

\[
B = \frac{F_m}{IL} = \frac{F_m}{(\Delta V/R)L} = \frac{(12 \Omega)(5.9 \times 10^{-2} \text{ N})}{(24 \text{ V})(5.0 \times 10^{-2} \text{ m})} = 0.59 \text{ T}
\]

19.75 The magnetic force is very small in comparison to the weight of the ball, so we treat the motion as that of a freely falling body. Then, as the ball approaches the ground, it has velocity components with magnitudes of

\[
v_x = v_{x_0} = 20.0 \text{ m/s}, \text{ and}
\]

\[
v_y = \sqrt{v_{y_0}^2 + 2a_y(\Delta y)} = \sqrt{0 + 2(-9.80 \text{ m/s}^2)(-20.0 \text{ m})} = 19.8 \text{ m/s}
\]

The velocity of the ball is perpendicular to the magnetic field and, just before it reaches the ground, has magnitude \( v = \sqrt{v_x^2 + v_y^2} = 28.1 \text{ m/s} \). Thus, the magnitude of the magnetic force is

\[
F_m = qvB \sin \theta
\]

\[
= (5.00 \times 10^{-6} \text{ C})(28.1 \text{ m/s})(0.0100 \text{ T}) \sin 90^\circ = 1.41 \times 10^{-4} \text{ N}
\]
(a) \[ B_1 = \frac{\mu_0 I_1}{2\pi d} = \frac{(4\pi \times 10^{-7} \text{ T} \cdot \text{m/A})(5.00 \text{ A})}{2\pi (0.100 \text{ m})} = 1.00 \times 10^{-5} \text{ T} \]

(b) \[ \frac{F_{21}}{\ell} = B_1 I_1 = (1.00 \times 10^{-5} \text{ T})(8.00 \text{ A}) = 8.00 \times 10^{-5} \text{ N directed toward wire 1} \]

(c) \[ B_2 = \frac{\mu_0 I_2}{2\pi d} = \frac{(4\pi \times 10^{-7} \text{ T} \cdot \text{m/A})(8.00 \text{ A})}{2\pi (0.100 \text{ m})} = 1.60 \times 10^{-5} \text{ T} \]

(d) \[ \frac{F_{21}}{\ell} = B_2 I_1 = (1.60 \times 10^{-5} \text{ T})(5.00 \text{ A}) = 8.00 \times 10^{-5} \text{ N directed toward wire 2} \]