Problem Solutions

19.1 The direction in parts (a) through (d) is found by use of the right hand rule. You must remember that the electron is negatively charged and thus experiences a force in the direction exactly opposite that predicted by the right hand rule for a positively charged particle.

(a) $\boxed{\text{horizontal and due east}}$ (b) $\boxed{\text{horizontal and 30° N of E}}$

(c) $\boxed{\text{horizontal and due east}}$ (d) $\boxed{\text{zero force}}$, $F = qvB\sin\theta = qvB\sin(180°) = 0$

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

(a′) $\boxed{\text{in plane of page and to left}}$ (b′) $\boxed{\text{into the page}}$

(c′) $\boxed{\text{out of the page}}$ (d′) $\boxed{\text{in plane of page and toward the top}}$

(e′) $\boxed{\text{into the page}}$ (f′) $\boxed{\text{out of the page}}$

(b) For a negatively charged particle, the direction of the force is exactly opposite what the right hand rule predicts for positive charges. Thus, the answers for part (b) are $\boxed{\text{reversed from those given in part (a)}}$.

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

(a) $\boxed{\text{into the page}}$ (b) $\boxed{\text{toward the right}}$ (c) $\boxed{\text{toward bottom of page}}$

19.4 Hold the right hand with the fingers in the direction of $\vec{\mathbf{v}}$ so that as you close your hand, the fingers move toward the direction of $\vec{\mathbf{B}}$. 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) $\boxed{\text{toward top of page}}$ (b) $\boxed{\text{out of the page}}$, since the charge is negative.

(c) $\boxed{\text{zero force}}$ (d) $\boxed{\text{into the page}}$

19.5 Gravitational force:

$$F_g = mg = \left(9.11\times10^{-31}\ \text{kg}\right)\left(9.80\ \text{m/s}^2\right) = 8.93\times10^{-30}\ \text{N downward}$$

Electric force:

$$F_e = qE = \left(-1.60\times10^{-19}\ \text{C}\right)\left(-100\ \text{N/C}\right) = 1.60\times10^{-17}\ \text{N upward}$$

Magnetic force:

$$F_m = qvB\sin\theta = \left(-1.60\times10^{-19}\ \text{C}\right)\left(6.00\times10^{6}\ \text{m/s}\right)\left(50.0\times10^{-6}\ \text{T}\right)\sin(90.0^\circ)$$

$$= 4.80\times10^{-17}\ \text{N in direction opposite right hand rule prediction}$$

$$F_m = \boxed{4.80\times10^{-17}\ \text{N downward}}$$

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

$$F = \left(1.60\times10^{-19}\ \text{C}\right)\left(6.2\times10^{6}\ \text{m/s}\right)\left(50.0\times10^{-6}\ \text{T}\right)\sin(90.0^\circ) = \boxed{4.96\times10^{-17}\ \text{N}}$$

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

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

$$m\frac{v^2}{r} = qvB\sin 90^\circ \text{, or } v = \frac{qBr}{m} \quad \text{where } r = R_E + 1000\ \text{km} = 7.38\times10^{6}\ \text{m}$$

$$v = \frac{\left(1.60\times10^{-19}\ \text{C}\right)\left(4.00\times10^{-8}\ \text{T}\right)\left(7.38\times10^{6}\ \text{m}\right)}{1.67\times10^{-27}\ \text{kg}} = \boxed{2.83\times10^{7}\ \text{m/s}}$$

If $\vec{\mathbf{v}}$ is $\boxed{\text{toward the west}}$ and $\vec{\mathbf{B}}$ is northward, $\vec{\mathbf{F}}$ will be directed downward as required.

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

$$v = \sqrt{\frac{2e(\Delta V)}{m}} = \sqrt{\frac{2(1.60\times10^{-19}\ \text{C})(2\,400\ \text{V})}{9.11\times10^{-31}\ \text{kg}}} = 2.90\times10^{7}\ \text{m/s}$$

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

$$F_{max} = |q|vB\sin 90°$$

$$= (1.60\times10^{-19}\ \text{C})(2.90\times10^{7}\ \text{m/s})(1.70\ \text{T}) = \boxed{7.90\times10^{-12}\ \text{N}}$$

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

$$F_{min} = |q|vB\sin 0° = \boxed{0}$$

19.9 $$B = \frac{F}{qv} = \frac{ma}{qv} = \frac{(1.67\times10^{-27}\ \text{kg})(2.0\times10^{13}\ \text{m/s}^2)}{(1.60\times10^{-19}\ \text{C})(1.0\times10^{7}\ \text{m/s})} = \boxed{0.021\ \text{T}}$$

The right hand rule shows that $\vec{\mathbf{B}}$ must be in $\boxed{\text{the } -y \text{ direction}}$ to yield a force in the $+x$ direction when $\vec{\mathbf{v}}$ is in the $+z$ direction.

19.10 The force on a single ion is

$$F_1 = qvB\sin\theta$$

$$= (1.60\times10^{-19}\ \text{C})(0.851\ \text{m/s})(0.254\ \text{T})\sin(51.0°) = 2.69\times10^{-20}\ \text{N}$$

The total number of ions present is

$$N = \left(3.00\times10^{20}\ \frac{\text{ions}}{\text{cm}^3}\right)(100\ \text{cm}^3) = 3.00\times10^{22}$$

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

$$F = N\cdot F_1 = (3.00\times10^{22})(2.69\times10^{-20}\ \text{N}) = \boxed{806\ \text{N}}$$

19.11 From $F = BIL\sin\theta$, the magnetic field is

$$B = \frac{F/L}{I\sin\theta} = \frac{0.12\ \text{N/m}}{(15\ \text{A})\sin 90^\circ} = \boxed{8.0\times10^{-3}\ \text{T}}$$

The direction of $\vec{\mathbf{B}}$ must be $\boxed{\text{the } +z \text{ direction}}$ to have $\vec{\mathbf{F}}$ in the $-y$ direction when $\vec{\mathbf{I}}$ is in the $+x$ direction.

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) $\boxed{\text{to the left}}$ (b) $\boxed{\text{into the page}}$ (c) $\boxed{\text{out of the page}}$

(d) $\boxed{\text{toward top of page}}$ (e) $\boxed{\text{into the page}}$ (f) $\boxed{\text{out of the page}}$

19.13 Use the right hand rule, 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) $\boxed{\text{into the page}}$ (b) $\boxed{\text{toward the right}}$ (c) $\boxed{\text{toward the bottom of the page}}$

19.14 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

$$\frac{F}{\ell} = BI\sin\theta = \left(\frac{m}{\ell}\right)g \qquad \text{giving} \qquad B = \left(\frac{m}{\ell}\right)\frac{g}{I\sin\theta}$$

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

$$B_{\min} = \left(\frac{m}{\ell}\right)\frac{g}{I\sin 90.0^\circ} = \left[0.500\ \frac{\text{g}}{\text{cm}}\left(\frac{1\ \text{kg}}{10^3\ \text{g}}\right)\left(\frac{10^2\ \text{cm}}{1\ \text{m}}\right)\right]\frac{9.80\ \text{m/s}^2}{(2.00\ \text{A})(1)} = \boxed{0.245\ \text{T}}$$

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 $\boxed{\text{eastward}}$.

19.15 $F = BIL\sin\theta = (0.300\ \text{T})(10.0\ \text{A})(5.00\ \text{m})\sin(30.0°) = \boxed{7.50\ \text{N}}$

19.16 (a) The magnitude is

$$F = BIL\sin\theta = \left(0.60\times10^{-4}\ \text{T}\right)(15\ \text{A})(10.0\ \text{m})\sin(90°) = \boxed{9.0\times10^{-3}\ \text{N}}$$

$\vec{\mathbf{F}}$ is perpendicular to $\vec{\mathbf{B}}$. Using the right hand rule, the orientation of $\vec{\mathbf{F}}$ is found to be $\boxed{\text{15° above the horizontal in the northward direction}}$.

(b) $F = BIL\sin\theta = \left(0.60\times10^{-4}\ \text{T}\right)(15\ \text{A})(10.0\ \text{m})\sin(165°) = \boxed{2.3\times10^{-3}\ \text{N}}$

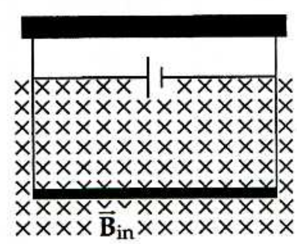
and, from the right hand rule, the direction is $\boxed{\text{horizontal and due west}}$

19.17 For minimum field, $\vec{\mathbf{B}}$ should be perpendicular to the wire. If the force is to be northward, the field must be directed $\boxed{\text{downward}}$.

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

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

19.18 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,



$$\frac{\left|\vec{\mathbf{F}}_m\right|}{L} = BI = \frac{mg}{L}\text{, or}$$

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

From the right hand rule, the current must be $\boxed{\text{to the right}}$ if the force is to be upward when the magnetic field is into the page.

19.19 For the wire to move upward at constant speed, the net force acting on it must be zero. Thus, $BIL\sin\theta = mg$ and for minimum field $\theta = 90°$. The minimum field is

$$B = \frac{mg}{IL} = \frac{(0.015\text{ kg})(9.80\text{ m/s}^2)}{(5.0\text{ A})(0.15\text{ m})} = \boxed{0.20\text{ T}}$$

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

19.20 The magnitude of the magnetic force exerted on a current-carrying conductor in a magnetic field is given by $F = BI\ell\sin\theta$, where B is the magnitude of the field, ℓ is the length of the conductor, I is the current in the conductor, and θ is the angle the conductor makes with the direction of the field. In this case,

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

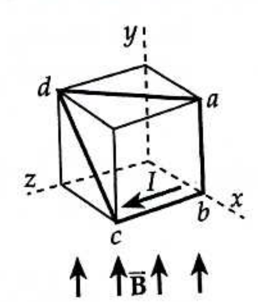
(a) If $\theta = 60.0°$, then $\sin\theta = 0.866$ and $F = \boxed{4.73\text{ N}}$

(b) If $\theta = 90.0°$, then $\sin\theta = 1.00$ and $F = \boxed{5.46\text{ N}}$

(c) If $\theta = 120°$, then $\sin\theta = 0.866$ and $F = \boxed{4.73\text{ N}}$

19.21 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. The results of applying these to each of the four segments are summarized below.

Segment	L (m)	θ	F (N)	Direction
ab	0.400	180°	0	–
bc	0.400	90.0°	0.040 0	negative x
cd	$0.400\sqrt{2}$	45.0°	0.040 0	negative z
da	$0.400\sqrt{2}$	90.0°	0.056 6	parallel to x-z plane at 45° to both $+x$ and $+z$ directions



19.22 The magnitude of the torque is $\tau = NBIA\sin\theta$, where θ 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 $r = \dfrac{1.00\text{ m}}{\pi}$ and the area is $A = \pi r^2 = \dfrac{1}{\pi}\text{ m}^2$.

Thus, $\tau = (1)(0.800\text{ T})(17.0\times10^{-3}\text{ A})\left(\dfrac{1}{\pi}\text{ m}^2\right)\sin 90.0° = \boxed{4.33\times10^{-3}\text{ N}\cdot\text{m}}$

19.23 The area is $A = \pi ab = \pi(0.200\text{ m})(0.150\text{ m}) = 0.094\,2\text{ m}^2$. Since the field is parallel to the plane of the loop, $\theta = 90.0°$ and the magnitude of the torque is

$$\tau = NBIA\sin\theta$$

$$= 8(2.00\times10^{-4}\text{ T})(6.00\text{ A})(0.094\,2\text{ m}^2)\sin 90.0° = \boxed{9.05\times10^{-4}\text{ N}\cdot\text{m}}$$

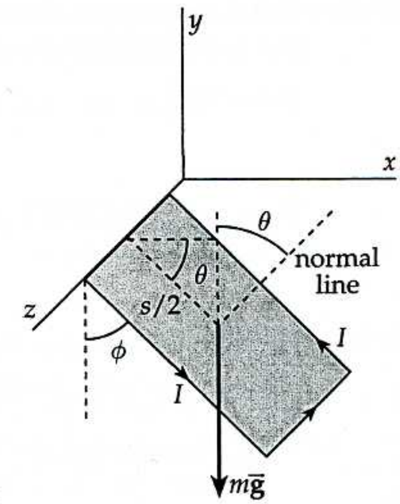
The torque is directed to make the left-hand side of the loop move toward you and the right-hand side move away.

19.24 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

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

With current in the $-y$ direction, the outside edge of the loop will experience a force directed out of the page ($+z$ direction) according to the right hand rule. Thus, the loop will rotate $\boxed{\text{clockwise as viewed from above}}$.

19.25 (a) Let θ 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 $\phi = 90.0° - \theta$. The number of turns on the loop is



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

The torque about the z axis due to gravity is $\tau_g = mg\left(\frac{s}{2}\cos\theta\right)$, where $s = 0.100$ 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, $\tau_m = \tau_g$ or $NBI(s^2)\sin\theta = mg(s\cos\theta)/2$. This reduces to

$$\tan\theta = \frac{mg}{2NBIs} = \frac{(0.100 \text{ kg})(9.80 \text{ m/s}^2)}{2(10.0)(0.010\,0 \text{ T})(3.40 \text{ A})(0.100 \text{ m})} = 14.4$$

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

(b) At equilibrium,

$$\tau_m = NBI(s^2)\sin\theta$$

$$= (10.0)(0.010\,0 \text{ T})(3.40 \text{ A})(0.100 \text{ m})^2 \sin(90.0° - 3.97°)$$

$$= \boxed{3.39 \times 10^{-3} \text{ N} \cdot \text{m}}$$

19.26 The resistance of the loop is

$$R = \frac{\rho L}{A} = \frac{(1.70\times10^{-8}\ \Omega\cdot\text{m})(8.00\ \text{m})}{1.00\times10^{-4}\ \text{m}^2} = 1.36\times10^{-3}\ \Omega$$

and the current in the loop is $I = \frac{\Delta V}{R} = \frac{0.100\ \text{V}}{1.36\times10^{-3}\ \Omega} = 73.5\ \text{A}$

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

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

19.27 The magnitude of the force a proton experiences as it moves perpendicularly to a magnetic field is

$$F = qvB\sin\theta = (+e)vB\sin(90.0°) = evB$$

This force is always directed perpendicular to the velocity of the proton and will supply the centripetal acceleration as the proton follows a circular path. Thus,

$$evB = m\frac{v^2}{r} \qquad \text{or} \qquad v = \frac{erB}{m}$$

and the time required for the proton to complete one revolution is

$$T = \frac{2\pi r}{v} = \frac{2\pi r}{erB/m} = \frac{2\pi m}{eB}$$

If it is observed that $T = 1.00\ \mu\text{s}$, the magnitude of the magnetic field is

$$B = \frac{2\pi m}{eT} = \frac{2\pi(1.67\times10^{-27}\ \text{kg})}{(1.60\times10^{-19}\ \text{C})(1.00\times10^{-6}\ \text{s})} = \boxed{6.56\times10^{-2}\ \text{T}}$$

19.28 Since the path is circular, the particle moves perpendicular to the magnetic field, and the magnetic force supplies the centripetal acceleration. Hence, $m\frac{v^2}{r} = qvB$, or $B = \frac{mv}{qr}$. But the momentum is given by $p = mv = \sqrt{2m(KE)}$, and the kinetic energy of this proton is $KE = \left(10.0\times10^6 \text{ eV}\right)\left(\frac{1.60\times10^{-19}\text{ J}}{1\text{ eV}}\right) = 1.60\times10^{-12}$ J. We then have

$$B = \frac{\sqrt{2m(KE)}}{qr} = \frac{\sqrt{2\left(1.67\times10^{-27}\text{ kg}\right)\left(1.60\times10^{-12}\text{ J}\right)}}{\left(1.60\times10^{-19}\text{ C}\right)\left(5.80\times10^{10}\text{ m}\right)} = \boxed{7.88\times10^{-12}\text{ T}}$$

19.29 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

$$F_m = F_e\text{, or } qvB = qE \text{ which reduces to } \boxed{v = E/B}$$

19.30 The speed of the particles emerging from the velocity selector is $v = E/B$ (see Problem 29). In the deflection chamber, the magnetic force supplies the centripetal acceleration, so $qvB = \frac{mv^2}{r}$, or $r = \frac{mv}{qB} = \frac{m(E/B)}{qB} = \frac{mE}{qB^2}$

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

$$r = \frac{\left(2.18\times10^{-26}\text{ kg}\right)\left(950\text{ V/m}\right)}{\left(1.60\times10^{-19}\text{ C}\right)\left(0.930\text{ T}\right)^2} = 1.50\times10^{-4}\text{ m} = \boxed{0.150\text{ mm}}$$

19.31 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

$$v = \sqrt{\frac{2q\left(V_i - V_f\right)}{m}} = \sqrt{\frac{2q(\Delta V)}{m}} = \sqrt{\frac{2\left(1.60\times10^{-19}\text{ C}\right)(250\text{ V})}{2.50\times10^{-26}\text{ kg}}} = 5.66\times10^4\text{ m/s}$$

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

or $$r = \frac{mv}{qB} = \frac{\left(2.50\times10^{-26}\text{ kg}\right)\left(5.66\times10^4\text{ m/s}\right)}{\left(1.60\times10^{-19}\text{ C}\right)(0.500\text{ T})} = 1.77\times10^{-2}\text{ m} = \boxed{1.77\text{ cm}}$$

19.32 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

$$\Delta d = 2\left(r_{238} - r_{235}\right) = \frac{2v}{qB}\left(m_{238} - m_{235}\right)$$

$$= \frac{2\left(3.00\times10^{5}\ \text{m/s}\right)}{\left(1.60\times10^{-19}\ \text{C}\right)\left(0.600\ \text{T}\right)}\left[(238\ \text{u} - 235\ \text{u})\left(1.66\times10^{-27}\ \frac{\text{kg}}{\text{u}}\right)\right]$$

or $$\Delta d = 3.11\times10^{-2}\ \text{m} = \boxed{3.11\ \text{cm}}$$

19.33 In the perfectly elastic, head-on collision between the α-particle and the initially stationary proton, conservation of momentum requires that $m_p v_p + m_\alpha v_\alpha = m_\alpha v_0$ while conservation of kinetic energy also requires that $v_0 - 0 = -\left(v_\alpha - v_p\right)$ or $v_p = v_\alpha + v_0$. Using the fact that $m_\alpha = 4m_p$ and combining these equations gives

$$m_p\left(v_\alpha + v_0\right) + \left(4m_p\right)v_\alpha = \left(4m_p\right)v_0 \qquad \text{or} \qquad v_\alpha = 3v_0/5$$

and $$v_p = \left(3v_0/5\right) + v_0 = 8v_0/5 \qquad \text{Thus,} \quad v_\alpha = \frac{3}{5}v_0 = \frac{3}{5}\left(\frac{5}{8}v_p\right) = \frac{3}{8}v_p$$

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*, and that of the alpha particle is *r*, we have

$$q_p v_p B = m_p \frac{v_p^2}{R} \qquad \text{or} \qquad R = \frac{m_p v_p}{q_p B} = \frac{m_p v_p}{eB}$$

and $$q_\alpha v_\alpha B = m_\alpha \frac{v_\alpha^2}{r} \qquad \text{or} \qquad r = \frac{m_\alpha v_\alpha}{q_\alpha B} = \frac{\left(4m_p\right)\left(3v_p/8\right)}{(2e)B} = \frac{3}{4}\left(\frac{m_p v_p}{eB}\right) = \boxed{\frac{3}{4}R}$$

19.34 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) $\boxed{\text{toward the left}}$ (b) $\boxed{\text{out of page}}$ (c) $\boxed{\text{lower left to upper right}}$

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

$$B = \frac{\mu_0 I}{2\pi r} = \frac{(4\pi \times 10^{-7}\ \text{T}\cdot\text{m/A})(1.00\times 10^{4}\ \text{A})}{2\pi(100\ \text{m})} = 2.00\times 10^{-5}\ \text{T} = \boxed{20.0\ \mu\text{T}}$$

19.36 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

$$\boxed{\text{conventional current is downward or negative charge flows upward}}.$$

The magnitude of the current is found from $B = \mu_0 I/2\pi r$ as

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

19.37 From $B = \mu_0 I/2\pi r$, the required distance is

$$r = \frac{\mu_0 I}{2\pi B} = \frac{(4\pi\times 10^{-7}\ \text{T}\cdot\text{m/A})(20\ \text{A})}{2\pi(1.7\times 10^{-3}\ \text{T})} = 2.4\times 10^{-3}\ \text{m} = \boxed{2.4\ \text{mm}}$$

19.38 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,

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

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

or $B_{net} = \boxed{40.0\ \mu\text{T into the page}}$

(b) At point P_1, $$B_{net} = +B_1 - B_2 = \frac{\mu_0}{2\pi}\left[\frac{I_1}{r_1} - \frac{I_2}{r_2}\right]$$

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

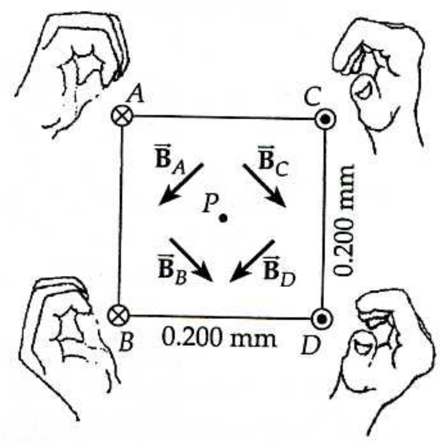
(c) At point P_2, $B_{net} = -B_1 + B_2 = \frac{\mu_0}{2\pi}\left[-\frac{I_1}{r_1} + \frac{I_2}{r_2}\right]$

$$B_{net} = \frac{(4\pi \times 10^{-7}\ \text{T}\cdot\text{m/A})}{2\pi}\left[-\frac{5.00\ \text{A}}{0.300\ \text{m}} + \frac{5.00\ \text{A}}{0.200\ \text{m}}\right]$$

$$= \boxed{1.67\ \mu\text{T out of page}}$$

19.39 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

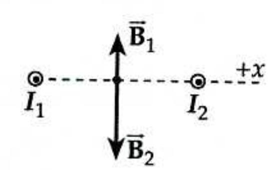
$$B = \frac{\mu_0 I}{2\pi r} = \frac{(4\pi \times 10^{-7}\ \text{T}\cdot\text{m/A})(5.00\ \text{A})}{2\pi(0.141\ \text{m})} = 7.07\ \mu\text{T}$$

Carrying currents into the page, the field A produces at P is directed to the left and down at –135°, while B creates a field to the right and down at – 45°. Carrying currents toward you, C produces a field downward and to the right at – 45°, while D's contribution is downward and to the left. The horizontal components of these equal magnitude contributions cancel in pairs, while the vertical components all add. The total field is then

$$B_{net} = 4(7.07\ \mu\text{T})\sin 45.0° = \boxed{20.0\ \mu\text{T toward the bottom of the page}}$$

19.40 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

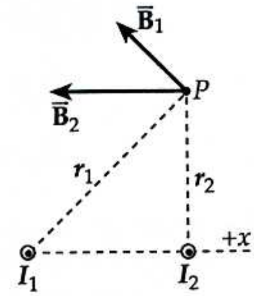


$$B_{net} = +B_{1y} - B_{2y} = \mu_0(I_1 - I_2)/2\pi r$$

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

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

(b) At point P, $r_1 = (0.200\text{ m})\sqrt{2}$ and B_1 is directed at $\theta_1 = +135°$.



The magnitude of B_1 is

$$B_1 = \frac{\mu_0 I_1}{2\pi r_1} = \frac{(4\pi\times10^{-7}\text{ T}\cdot\text{m/A})(3.00\text{ A})}{2\pi(0.200\sqrt{2}\text{ m})} = 2.12\ \mu\text{T}$$

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

$$B_2 = \frac{\mu_0 I_2}{2\pi r_2} = \frac{(4\pi\times10^{-7}\text{ T}\cdot\text{m/A})(5.00\text{ A})}{2\pi(0.200\text{ m})} = 5.00\ \mu\text{T}$$

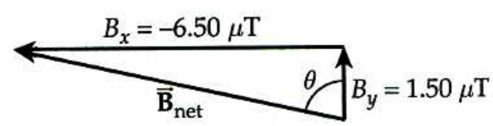
Therefore, the components of the net field at point P are:

$$B_x = B_1\cos135° + B_2\cos180°$$

$$= (2.12\ \mu\text{T})\cos135° + (5.00\ \mu\text{T})\cos180° = -6.50\ \mu\text{T}$$

and $$B_y = B_1\sin135° + B_2\sin180° = (2.12\ \mu\text{T})\sin135° + 0 = +1.50\ \mu\text{T}$$

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



$$\theta = \tan^{-1}\left(\frac{|B_x|}{B_y}\right) = \tan^{-1}\left(\frac{6.50\ \mu\text{T}}{1.50\ \mu\text{T}}\right) = 77.0°$$

or $\vec{B}_{net} = \boxed{6.67\ \mu\text{T at } 77.0° \text{ to the left of vertical}}$

19.41 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, $B_{net} = +B_1 - B_2 = \dfrac{\mu_0 I_1}{2\pi r_1} - \dfrac{\mu_0 I_2}{2\pi r_2} = \dfrac{\mu_0}{2\pi}\left(\dfrac{I_1}{r_1} - \dfrac{I_2}{r_2}\right)$

or $$B_{net} = \frac{(4\pi\times10^{-7}\text{ T}\cdot\text{m/A})}{2\pi}\left(\frac{7.00\text{ A}}{3.00\text{ m}} - \frac{6.00\text{ A}}{4.00\text{ m}}\right) = +1.67\times10^{-7}\text{ T}$$

$B_{net} = \boxed{0.167\ \mu\text{T out of the page}}$

19.42 Since the proton moves with constant velocity, the net force acting on it is zero. Thus, the magnetic force due to the current in the wire must be counterbalancing the weight of the proton, or $qvB = mg$ where $B = \mu_0 I/2\pi d$. This gives

$\dfrac{qv\mu_0 I}{2\pi d} = mg$, or the distance the proton is above the wire must be

$$d = \frac{qv\mu_0 I}{2\pi mg} = \frac{(1.60\times10^{-19}\text{ C})(2.30\times10^{4}\text{ m/s})(4\pi\times10^{-7}\text{ T}\cdot\text{m/A})(1.20\times10^{-6}\text{ A})}{2\pi(1.67\times10^{-27}\text{ kg})(9.80\text{ m/s}^2)}$$

$$d = 5.40\times10^{-2}\text{ m} = \boxed{5.40\text{ cm}}$$

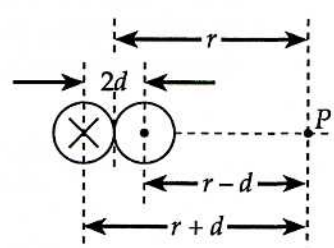
19.43 (a) From $B = \mu_0 I/2\pi r$, observe that the field is inversely proportional to the distance from the conductor. Thus, the field will have one-tenth its original value if the distance is increased by a factor of 10. The required distance is then $r' = 10r = 10(0.400\text{ m}) = \boxed{4.00\text{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

(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

$$B_{net} = \frac{\mu_0 I}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_2}\right) = \frac{(4\pi\times10^{-7}\text{ T}\cdot\text{m/A})(2.00\text{ A})}{2\pi}\left(\frac{1}{0.3985\text{ m}} - \frac{1}{0.4015\text{ m}}\right)$$

$$= 7.50\times10^{-9}\text{ T} = \boxed{7.50\text{ nT}}$$

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



$$B_{net} = \frac{\mu_0 I}{2\pi}\left(\frac{1}{r-d} - \frac{1}{r+d}\right) = \frac{\mu_0 I}{2\pi}\left(\frac{2d}{r^2 - d^2}\right)$$

$$7.50\times10^{-10}\text{ T} = \frac{(4\pi\times10^{-7}\text{ T}\cdot\text{m/A})(2.00\text{ A})}{2\pi}\left(\frac{3.00\times10^{-3}\text{ m}}{r^2 - 2.25\times10^{-6}\text{ m}^2}\right)$$

so $r = \boxed{1.26\text{ m}}$

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

(d) The cable creates $\boxed{\text{zero}}$ field at exterior points, since a loop in Ampère's law encloses zero total current.

19.44 (a) $$\frac{F}{L}=\frac{\mu_0 I_1 I_2}{2\pi d}=\frac{\left(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A}\right)(10.0\ \text{A})^2}{2\pi(0.100\ \text{m})}$$

$$=\boxed{2.00\times10^{-4}\ \text{N/m}\ \ (\text{attraction})}$$

(b) The magnitude remains the same as calculated in (a), but the wires are repelled. Thus, $\frac{F}{L}=\boxed{2.00\times10^{-4}\ \text{N/m}\ \ (\text{repulsion})}$

19.45 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, $\frac{F}{L}=\frac{\mu_0 I_1 I_2}{2\pi d}=0.080\ \text{N/m}$, and the distance between the wires will be

$$d=\frac{\mu_0 I_1 I_2}{2\pi(0.080\ \text{N/m})}=\frac{\left(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A}\right)(60.0\ \text{A})(30.0\ \text{A})}{2\pi(0.080\ \text{N/m})}$$

$$=4.5\times10^{-3}\ \text{m}=\boxed{4.5\ \text{mm}}$$

19.46 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

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

or $$F_{net}=\frac{\left(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A}\right)(5.00\ \text{A})(10.0\ \text{A})(0.450\ \text{m})}{2\pi}\left(\frac{1}{0.100\ \text{m}}-\frac{1}{0.250\ \text{m}}\right)$$

$$=+2.70\times10^{-5}\ \text{N}=\boxed{2.70\times10^{-5}\ \text{N to the left}}$$

19.47 The magnetic field inside a long solenoid is $B=\mu_0 nI=\mu_0\left(\frac{N}{L}\right)I$. Thus, the required current is

$$I=\frac{BL}{\mu_0 N}=\frac{\left(1.00\times10^{-4}\ \text{T}\right)(0.400\ \text{m})}{\left(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A}\right)(1\,000)}=3.18\times10^{-2}\ \text{A}=\boxed{31.8\ \text{mA}}$$

19.48 (a) From $R=\rho L/A$, the required length of wire to be used is

$$L=\frac{R\cdot A}{\rho}=\frac{(5.00\ \Omega)\left[\pi\left(0.500\times10^{-3}\ \text{m}\right)^2/4\right]}{1.70\times10^{-8}\ \Omega\cdot\text{m}}=57.7\ \text{m}$$

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

$$N=\frac{L}{2\pi r}=\frac{57.7\ \text{m}}{2\pi\left(1.00\times10^{-2}\ \text{m}\right)}=\boxed{919}$$

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

$$n=\frac{B}{\mu_0 I}=\frac{4.00\times10^{-2}\ \text{T}}{\left(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A}\right)(4.00\ \text{A})}=7.96\times10^{3}\ \text{turns/m}$$

Thus, the required length of the solenoid is

$$\frac{N}{n}=\frac{919\ \text{turns}}{7.96\times10^{3}\ \text{turns/m}}=0.115\ \text{m}=\boxed{11.5\ \text{cm}}$$

19.49 The magnetic field inside the solenoid is

$$B=\mu_0 nI_1=\left(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A}\right)\left[\left(30\ \frac{\text{turns}}{\text{cm}}\right)\left(\frac{100\ \text{cm}}{1\ \text{m}}\right)\right](15.0\ \text{A})=5.65\times10^{-2}\ \text{T}$$

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

$$F=BI_2 L\sin 90.0^\circ=\left(5.65\times10^{-2}\ \text{T}\right)(0.200\ \text{A})\left(2.00\times10^{-2}\ \text{m}\right)=\boxed{2.26\times10^{-4}\ \text{N}}$$

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

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

$$B = \frac{mv}{qr} = \frac{(9.11\times10^{-31}\text{ kg})(1.0\times10^{4}\text{ m/s})}{(1.60\times10^{-19}\text{ C})(2.0\times10^{-2}\text{ m})} = 2.847\times10^{-6}\text{ T} = \boxed{2.8\ \mu\text{T}}$$

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

$$I = \frac{B}{\mu_0 n} = \frac{2.847\times10^{-6}\text{ T}}{(4\pi\times10^{-7}\text{ T}\cdot\text{m/A})\left[(25\text{ turns/cm})(100\text{ cm/1 m})\right]}$$

$$= 9.1\times10^{-4}\text{ A} = \boxed{0.91\text{ mA}}$$

19.51 When the plane of the coil makes an angle of 35° with the field direction, the perpendicular to the plane of the coil makes an angle of $\theta = 90° - 35° = 55°$ with the magnetic field.

Thus, the torque exerted on the loop is

$$\tau = NBIA\sin\theta = (1)(0.30\text{ T})(25\text{ A})\left[\pi(0.30\text{ m})^2\right]\sin 55° = \boxed{1.7\text{ N}\cdot\text{m}}$$

19.52 Since the magnetic force must supply the centripetal acceleration, $qvB = mv^2/r$ or the radius of the path is $r = mv/qB$.

(a) The time for the electron to travel the semicircular path (of length πr) is

$$t = \frac{\pi r}{v} = \frac{\pi}{v}\left(\frac{mv}{qB}\right) = \frac{\pi m}{qB} = \frac{\pi(9.11\times10^{-31}\text{ kg})}{(1.60\times10^{-19}\text{ C})(0.010\,0\text{ T})}$$

$$= 1.79\times10^{-9}\text{ s} = \boxed{1.79\text{ ns}}$$

(b) The radius of the semicircular path is 2.00 cm. From $r = mv/qB$, the momentum of the electron is $p = mv = qBr$, and the kinetic energy is

$$KE = \tfrac{1}{2}mv^2 = \frac{(mv)^2}{2m} = \frac{q^2B^2r^2}{2m} = \frac{\left(1.60\times10^{-19}\text{ C}\right)^2\left(0.010\,0\text{ T}\right)^2\left(2.00\times10^{-2}\text{ m}\right)^2}{2\left(9.11\times10^{-31}\text{ kg}\right)}$$

$$KE = \left(5.62\times10^{-16}\text{ J}\right)\left(\frac{1\text{ keV}}{1.60\times10^{-16}\text{ J}}\right) = \boxed{3.51\text{ keV}}$$

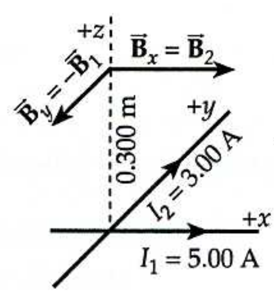
19.53 Assume wire 1 is along the x axis and wire 2 along the y axis.

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

$$B = B_1 - B_2 = \frac{\mu_0}{2\pi}\left(\frac{I_1}{r_1} - \frac{I_2}{r_2}\right) = \frac{\left(4\pi\times10^{-7}\text{ T}\cdot\text{m/A}\right)}{2\pi}\left(\frac{5.00\text{ A}}{0.400\text{ m}} - \frac{3.00\text{ A}}{0.300\text{ m}}\right)$$

$$= 5.00\times10^{-7}\text{ T} = \boxed{0.500\ \mu\text{T out of the page}}$$

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



$$B_y = -B_1 = -\frac{\mu_0 I_1}{2\pi r}$$

$$= -\frac{\left(4\pi\times10^{-7}\text{ T}\cdot\text{m/A}\right)(5.00\text{ A})}{2\pi(0.300\text{ m})} = -3.33\times10^{-6}\text{ T}$$

and $$B_x = B_2 = \frac{\mu_0 I_2}{2\pi r} = \frac{\left(4\pi\times10^{-7}\text{ T}\cdot\text{m/A}\right)(3.00\text{ A})}{2\pi(0.300\text{ m})} = 2.00\times10^{-6}\text{ T}$$

The resultant field is

$$B = \sqrt{B_x^2 + B_y^2} = 3.89\times10^{-6}\text{ T at } \theta = \tan^{-1}\left(\frac{B_y}{B_x}\right) = -59.0^\circ$$

or $\vec{\mathbf{B}} = \boxed{3.89\ \mu\text{T at } 59.0^\circ \text{ clockwise from } +x \text{ direction}}$

19.54 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 $BIL = \mu_k(mg)$, or

$$B = \frac{\mu_k(mg)}{IL} = \frac{(0.100)(0.200\ \text{kg})(9.80\ \text{m/s}^2)}{(10.0\ \text{A})(0.500\ \text{m})} = \boxed{3.92\times10^{-2}\ \text{T}}$$

19.55 The magnetic force acting on each type particle supplies the centripetal acceleration for that particle. Thus, $qvB = mv^2/r$ or $r = mv/qB$.

After completing one half of the circular paths, the two types of particle are separated by the difference in the diameters of the two paths. Therefore,

$$\Delta d = 2(r_2 - r_1) = \frac{2v}{qB}(m_2 - m_1)$$

$$= \frac{2(1.00\times10^5\ \text{m/s})}{(1.60\times10^{-19}\ \text{C})(0.200\ \text{T})}\left[(23.4-20.0)\times10^{-27}\ \text{kg}\right]$$

$$= 2.13\times10^{-2}\ \text{m} = \boxed{2.13\ \text{cm}}$$

19.56 Let the leftmost wire be wire 1 and the rightmost be wire 2.

(a) At point *C*, B_1 is directed out of the page and B_2 is into the page. If the net field is zero, then $B_1 = B_2$, or

$$\frac{\mu_0 I_1}{2\pi r_1} = \frac{\mu_0 I_2}{2\pi r_2}, \text{ giving } I_1 = I_2\left(\frac{r_1}{r_2}\right) = (10.0\ \text{A})\left(\frac{15.0\ \text{cm}}{5.00\ \text{cm}}\right) = \boxed{30.0\ \text{A}}$$

(b) At point *A*, B_1 and B_2 are both directed out of the page, so

$$B_{net} = B_1 + B_2 = \frac{\mu_0}{2\pi r}(I_1 + I_2) = \frac{(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A})}{2\pi(5.00\times10^{-2}\ \text{m})}(30.0\ \text{A}+10.0\ \text{A})$$

$$= \boxed{1.60\times10^{-4}\ \text{T out of the page}}$$

19.57 (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

$$qvB = qE = q(\Delta V/d)$$

$$\text{or } v = \frac{\Delta V}{Bd} = \frac{160\times10^{-6}\ \text{V}}{(0.040\,0\ \text{T})(3.00\times10^{-3}\ \text{m})} = \boxed{1.33\ \text{m/s}}$$

(b) The magnetic field is directed from N to S. If the charge carriers are negative moving in the direction of $\vec{\mathbf{v}}$, 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 $\vec{\mathbf{v}}$, 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 $\boxed{\text{does not depend on the charge of the ions}}$.

19.58 (a) Since the distance between them is so small in comparison to the radius of curvature, the hoops may be treated as long, straight, parallel wires. Because the currents are in opposite directions, the hoops repel each other. The magnetic force on the top loop is

$$F_m = \left(\frac{\mu_0 I_1 I_2}{2\pi d}\right)L = \frac{\mu_0 I^2(2\pi r)}{2\pi d} = \frac{\mu_0 I^2 r}{d}$$

$$= \frac{(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A})(140\ \text{A})^2(0.100\ \text{m})}{1.00\times10^{-3}\ \text{m}} = \boxed{2.46\ \text{N upward}}$$

(b) $\Sigma F_y = ma_y = F_m - mg$

$$\text{or } a_y = \frac{F_m}{m} - g = \frac{2.46\ \text{N}}{0.021\ \text{kg}} - 9.80\ \text{m/s}^2 = \boxed{107\ \text{m/s}^2\ \text{upward}}$$

19.59 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

$$v_x = v_{0x} = 20.0 \text{ m/s, and}$$

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

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

$$F_m = qvB\sin\theta$$

$$= (5.00\times10^{-6} \text{ C})(28.1 \text{ m/s})(0.010\,0 \text{ T})\sin 90.0° = \boxed{1.41\times10^{-6} \text{ N}}$$

19.60 We are given that the field at points on the axis of the disk varies as $B = k/h^3$, where k is a constant and h is the distance from the midplane of the disk. At the surface of the disk,

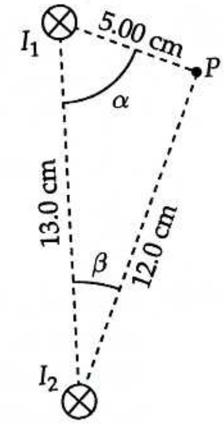
$$B = 5.0\times10^{-3} \text{ T} \qquad \text{and} \qquad h = \frac{thickness}{2} = \frac{1.0 \text{ mm}}{2} = 0.50 \text{ mm}$$

Thus, $k = Bh^3 = (5.0\times10^{-3} \text{ T})(0.50 \text{ mm})^3$. The distance <u>from the center plane</u> of the disk to the height where $B = 5.0\times10^{-5}$ T is then

$$h = \left[\frac{k}{B}\right]^{\frac{1}{3}} = \left[\frac{(5.0\times10^{-2} \text{ T})(0.50 \text{ mm})^3}{5.0\times10^{-5} \text{ T}}\right]^{\frac{1}{3}} = \left[1.0\times10^3\right]^{\frac{1}{3}}(0.50 \text{ mm}) = 5.0 \text{ mm}$$

The distance of this position <u>above the surface of the disk</u> is

$$x = h - \frac{thickness}{2} = 5.0 \text{ mm} - \frac{1.0 \text{ mm}}{2} = \boxed{4.5 \text{ mm}}$$

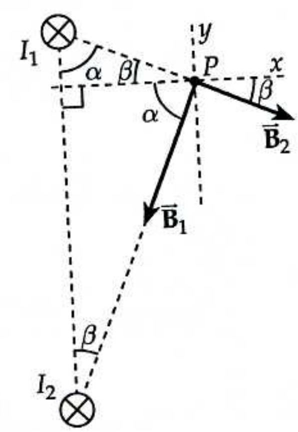


19.61 First, observe that $(5.00\text{ cm})^2 + (12.0\text{ cm})^2 = (13.0\text{ cm})^2$. Thus, the triangle shown in dashed lines is a right triangle giving

$$\alpha = \sin^{-1}\left(\frac{12.0\text{ cm}}{13.0\text{ cm}}\right) = 67.4°\text{, and } \beta = 90.0° - \alpha = 22.6°$$

At point P, the field due to wire 1 is

$$B_1 = \frac{\mu_0 I_1}{2\pi r_1} = \frac{(4\pi\times10^{-7}\text{ T}\cdot\text{m/A})(3.00\text{ A})}{2\pi(5.00\times10^{-2}\text{ m})} = 12.0\ \mu\text{T}$$



and it is directed from P toward wire 2, or to the left and at 67.4° below the horizontal. The field due to wire 2 has magnitude

$$B_2 = \frac{\mu_0 I_2}{2\pi r_2} = \frac{(4\pi\times10^{-7}\text{ T}\cdot\text{m/A})(3.00\text{ A})}{2\pi(12.00\times10^{-2}\text{ m})} = 5.00\ \mu\text{T}$$

and at P is directed away from wire 1 or to the right and at 22.6° below the horizontal.

Thus, $B_{1x} = -B_1\cos 67.4° = -4.62\ \mu\text{T}$ $\quad B_{1y} = -B_1 \sin 67.4° = -11.1\ \mu\text{T}$

$$B_{2x} = B_2\cos 22.6° = +4.62\ \mu\text{T} \quad B_{2y} = -B_2\sin 22.6° = -1.92\ \mu\text{T}$$

and $\quad B_x = B_{1x} + B_{2x} = 0$, while $B_y = B_{1y} + B_{2y} = -13.0\ \mu\text{T}$.

The resultant field at P is

$$\vec{\mathbf{B}} = \boxed{13.0\ \mu\text{T directed toward the bottom of the page}}$$

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

$$F_m = BIL\sin 90° = BIL$$

Thus, $\quad a_y = \frac{\Sigma F_y}{m} = \frac{F_m - mg}{m} = \frac{BI}{(m/L)} - g$, or

$$a_y = \frac{(4.0\times10^{-3}\text{ T})(2.0\text{ A})}{5.0\times10^{-4}\text{ kg/m}} - 9.80\text{ m/s}^2 = \boxed{6.2\text{ m/s}^2}$$

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

$$t = \sqrt{\frac{2(\Delta y)}{a_y}} = \sqrt{\frac{2(0.50\text{ m})}{6.2\text{ m/s}^2}} = \boxed{0.40\text{ s}}$$

19.63 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 $\theta = 45°$ in Figure 1.

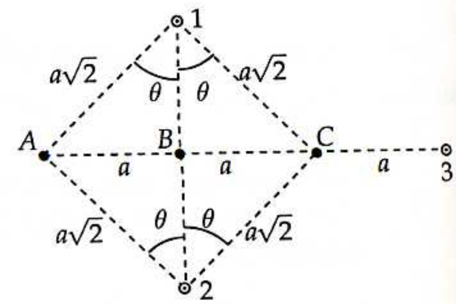


Figure 1

At point A, $B_1 = B_2 = \mu_0 I / 2\pi\left(a\sqrt{2}\right)$ or

$$B_1 = B_2 = \frac{\left(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A}\right)(2.0\text{ A})}{2\pi(0.010\text{ m})\sqrt{2}} = 28\ \mu\text{T}$$

and $B_3 = \dfrac{\mu_0 I}{2\pi(3a)} = \dfrac{\left(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A}\right)(2.0\text{ A})}{2\pi(0.030\text{ m})} = 13\ \mu\text{T}$

These field contributions are oriented as shown in Figure 2. Observe that the horizontal components of $\vec{\mathbf{B}}_1$ and $\vec{\mathbf{B}}_2$ cancel while their vertical components add to $\vec{\mathbf{B}}_3$. The resultant field at point A is then

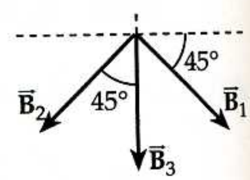


Figure 2

$$B_A = (B_1 + B_2)\cos 45° + B_3 = 53\ \mu\text{T}\text{, or}$$

$$\vec{\mathbf{B}}_A = \boxed{53\ \mu\text{T directed toward the bottom of the page}}$$

At point B, $\quad B_1 = B_2 = \dfrac{\mu_0 I}{2\pi a} = \dfrac{\left(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A}\right)(2.0\text{ A})}{2\pi(0.010\text{ m})} = 40\ \mu\text{T}$

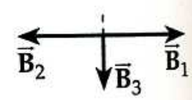


Figure 3

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

$$\vec{\mathbf{B}}_B = \vec{\mathbf{B}}_3 = \boxed{20\ \mu\text{T directed toward the bottom of the page}}$$

At point C, $B_1 = B_2 = \mu_0 I / 2\pi\left(a\sqrt{2}\right) = 28\ \mu\text{T}$ while $B_3 = \mu_0 I/2\pi a = 40\ \mu\text{T}$. These contributions are oriented as shown in Figure 4. Observe that the horizontal components of $\vec{\mathbf{B}}_1$ and $\vec{\mathbf{B}}_2$ cancel while their vertical components add to oppose $\vec{\mathbf{B}}_3$. The magnitude of the resultant field at C is

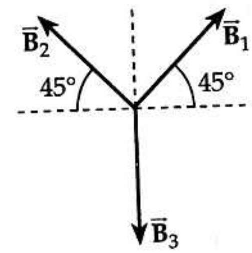


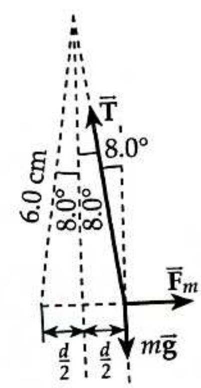
Figure 4

$$B_C = (B_1 + B_2)\sin 45° - B_3$$

$$= (56\ \mu\text{T})\sin 45° - 40\ \mu\text{T} = \boxed{0}$$

19.64 (a) Since one wire repels the other, the currents must be in $\boxed{\text{opposite directions}}$.

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



$$\Sigma F_y = 0 \Rightarrow T\cos 8.0° = mg$$

or $T = \dfrac{mg}{\cos 8.0°}$

$$\Sigma F_x = 0 \Rightarrow F_m = T\sin 8.0° = \left(\frac{mg}{\cos 8.0°}\right)\sin 8.0°$$

or $F_m = (mg)\tan 8.0°$. Thus, $\dfrac{\mu_0 I^2 L}{2\pi d} = (mg)\tan 8.0°$ which gives

$$I = \sqrt{\frac{d\left[(m/L)g\right]\tan 8.0°}{\mu_0/2\pi}}$$

Observe that the distance between the two wires is

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

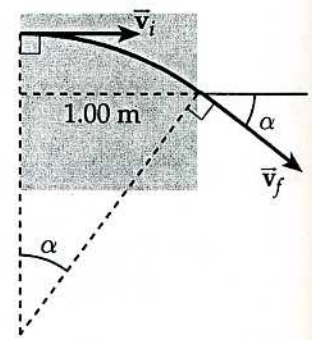
$$I = \sqrt{\frac{\left(1.7\times10^{-2}\text{ m}\right)(0.040\text{ kg/m})\left(9.80\text{ m/s}^2\right)\tan 8.0°}{2.0\times10^{-7}\text{ T}\cdot\text{m/A}}} = \boxed{68\text{ A}}$$

19.65 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 $r = mv/qB$. The speed of the particle may be written as $v = \sqrt{2(KE)/m}$, so the radius becomes

$$r = \frac{\sqrt{2m(KE)}}{qB} = \frac{\sqrt{2(1.67\times10^{-27}\text{ kg})(5.00\times10^{6}\text{ eV})(1.60\times10^{-19}\text{ J/eV})}}{(1.60\times10^{-19}\text{ C})(0.050\,0\text{ T})}$$

$$= 6.46\text{ m}$$



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

$$\alpha = \sin^{-1}\left(\frac{1.00\text{ m}}{r}\right) = \sin^{-1}\left(\frac{1.00\text{ m}}{6.46\text{ m}}\right) = \boxed{8.90^\circ}$$

(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

$$p_y = mv_y = -mv\sin\alpha = -m\left(\sqrt{2(KE)/m}\right)\sin\alpha = -\sin\alpha\sqrt{2m(KE)}$$

or $p_y = -\sin(8.90^\circ)\sqrt{2(1.67\times10^{-27}\text{ kg})(5.00\times10^{6}\text{ eV})(1.60\times10^{-19}\text{ J/eV})}$

$$= \boxed{-8.00\times10^{-21}\text{ kg}\cdot\text{m/s}}$$

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

$$k = \frac{F}{x} = \frac{mg}{x} = \frac{(10.0\times10^{-3}\text{ kg})(9.80\text{ m/s}^2)}{0.50\times10^{-2}\text{ m}} = 19.6\text{ N/m}$$

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

$$\Sigma F_y = F_m + mg = kx_{total}$$

Thus, the downward magnetic force acting on the wire is

$$F_m = kx_{total} - mg$$

$$= (19.6\ \text{N/m})(0.80\times10^{-2}\ \text{m}) - (10.0\times10^{-3}\ \text{kg})(9.80\ \text{m/s}^2)$$

$$= 5.9\times10^{-2}\ \text{N}$$

Since the magnetic force is given by $F_m = BIL\sin 90°$, the magnetic field is

$$B = \frac{F_m}{IL} = \frac{F_m}{(\Delta V/R)L} = \frac{(12\ \Omega)(5.9\times10^{-2}\ \text{N})}{(24\ \text{V})(5.0\times10^{-2}\ \text{m})} = \boxed{0.59\ \text{T}}$$

19.67 Each turn of wire occupies a length of the solenoid equal to the diameter of the wire. Thus, the number of turns on the solenoid is

$$N = \frac{L_{solenoid}}{d_{wire}} = \frac{75.0\ \text{cm}}{0.100\ \text{cm}} = 750$$

The length of wire required to make this number of turns on the solenoid is

$$\ell = N(circumference\ of\ solenoid) = N(\pi d_{solenoid}) = 750\pi(10.0\times10^{-2}\ \text{m}) = 75.0\pi\ \text{m}$$

and this copper wire has a resistance of

$$R = \rho_{\text{Cu}}\frac{\ell}{A_{wire}} = \rho_{\text{Cu}}\frac{4\ell}{\pi d_{wire}^2} = (1.7\times10^{-8}\ \Omega\cdot\text{m})\frac{4(75.0\pi\ \text{m})}{\pi(0.100\times10^{-2}\ \text{m})^2} = 5.10\ \Omega$$

Near the center of a long solenoid, the magnetic field is given by $B = \mu_0 nI = \mu_0 NI/L_{solenoid}$. Thus, if the field at the center of the solenoid is to be $B = 20.0\ \mu\text{T}$, the current in the solenoid must be

$$I = \frac{BL_{solenoid}}{\mu_0 N} = \frac{(20.0\times10^{-3}\ \text{T})(0.750\ \text{m})}{(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A})(750)} = 15.9\ \text{A}$$

and the power that must be delivered to the solenoid is

$$\mathcal{P} = I^2R = (15.9\ \text{A})^2(5.10\ \Omega) = 1.29\times10^3\ \text{W} = \boxed{1.29\ \text{kW}}$$

19.68 (a) A charged particle moving perpendicular to a magnetic field follows a circular arc with the magnetic force supplying the centripetal acceleration. Thus,

$$evB = m\frac{v^2}{r} \qquad \text{or} \qquad v = \frac{erB}{m}$$

The time required for the electron to traverse the semicircular path it follows while in the field is then

$$t = \frac{\textit{distance traveled}}{v} = \frac{\pi r}{erB/m} = \frac{\pi m}{eB} = \frac{\pi\left(9.11\times10^{-31}\text{ kg}\right)}{\left(1.60\times10^{-19}\text{ C}\right)\left(1.00\times10^{-3}\text{ T}\right)} = \boxed{1.79\times10^{-8}\text{ s}}$$

(b) The maximum penetration of the electron into the field equals the radius of the semicircular path followed while in the field. Therefore, $r = 2.00\text{ cm} = 2.00\times10^{-2}\text{ m}$ and

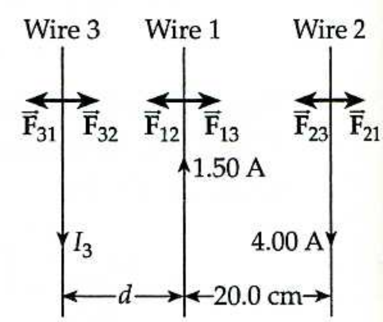
$$v = \frac{erB}{m} = \frac{\left(1.60\times10^{-19}\text{ C}\right)\left(2.00\times10^{-2}\text{ m}\right)\left(1.00\times10^{-3}\text{ T}\right)}{9.11\times10^{-31}\text{ kg}} = 3.51\times10^{6}\text{ m/s}$$

The kinetic energy is then

$$KE = \frac{1}{2}mv^2 = \frac{1}{2}\left(9.11\times10^{-31}\text{ kg}\right)\left(3.51\times10^{6}\text{ m/s}\right)^2 = 5.62\times10^{-18}\text{ J}$$

$$\text{or } KE = \left(5.62\times10^{-18}\text{ J}\right)\left(\frac{1\text{ eV}}{1.60\times10^{-19}\text{ J}}\right) = \boxed{35.1\text{ eV}}$$

19.69 With currents in opposite directions, wires 1 and 2 repel each another with forces $\vec{\mathbf{F}}_{12}$ and $\vec{\mathbf{F}}_{21}$ as shown in the sketch at the right. For these wires to be in equilibrium, wire 3 must exert a force directed to the right on wire 1 and a force to the left on wire 2. If wire 3 was between wires 1 and 2, the forces it exerts on these two wires would be in the same directions, contrary to what is needed. If wire 3 were to the right of wire 2, the force exerted on it by wire 2 (having the larger current and being nearer) would always exceed that exerted by wire 1. Hence, wire 3 could not be in equilibrium. Thus, we conclude that wire 3 must be to the left of wire 1 as shown above.



(a) For wire 3 to be in equilibrium, we must require that $F_{31} = F_{32}$, or

$$\frac{\mu_0 I_1 I_3 \ell}{2\pi d} = \frac{\mu_0 I_2 I_3 \ell}{2\pi(d + 20.0\text{ cm})} \qquad \text{giving} \qquad d + 20.0\text{ cm} = \left(\frac{I_2}{I_1}\right)d$$

Thus, $$d = \frac{20.0\text{ cm}}{(I_2/I_1) - 1} = \frac{20.0\text{ cm}}{(4.00\text{ A}/1.50\text{ A}) - 1} = \boxed{12.0\text{ cm}} \text{ (to the left of wire 1)}$$

(b) If wires 1 and 2 are to be in equilibrium, wire 3 must repel wire 1 and attract wire 2 as shown above. Hence, the current in wire 3 must be directed $\boxed{\text{downward}}$. The magnitude of this current can be determined by requiring that wire 1 be in equilibrium, or that $F_{13} = F_{12}$. This gives

$$\frac{\mu_0 I_1 I_3 \ell}{2\pi(12.0\text{ cm})} = \frac{\mu_0 I_1 I_2 \ell}{2\pi(20.0\text{ cm})} \quad \text{or}$$

$$I_3 = I_2\left(\frac{12.0\text{ cm}}{20.0\text{ cm}}\right) = (4.00\text{ A})(0.600) = \boxed{2.40\text{ A}}$$

Note that the same result could have been obtained by requiring that wire 2 be in equilibrium.

19.70 (a) $$B_1 = \frac{\mu_0 I_1}{2\pi d} = \frac{(4\pi\times10^{-7}\text{ T}\cdot\text{m/A})(5.00\text{ A})}{2\pi(0.100\text{ m})} = \boxed{1.00\times10^{-5}\text{ T}}$$

(b) $$\frac{F_{21}}{\ell} = B_1 I_2 = (1.00\times10^{-5}\text{ T})(8.00\text{ A}) = \boxed{8.00\times10^{-5}\text{ N directed toward wire 1}}$$

(c) $$B_2 = \frac{\mu_0 I_2}{2\pi d} = \frac{(4\pi\times10^{-7}\text{ T}\cdot\text{m/A})(8.00\text{ A})}{2\pi(0.100\text{ m})} = \boxed{1.60\times10^{-5}\text{ T}}$$

(d) $$\frac{F_{12}}{\ell} = B_2 I_1 = (1.60\times10^{-5}\text{ T})(5.00\text{ A}) = \boxed{8.00\times10^{-5}\text{ N directed toward wire 2}}$$