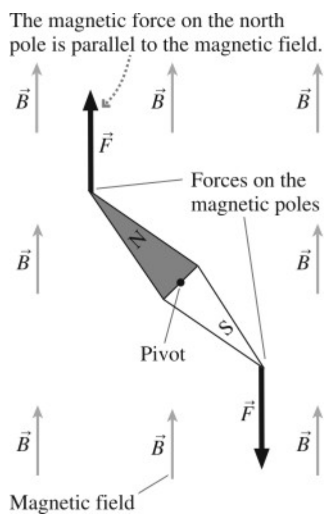
MAGNETIC FIELDS AND FORCES

24

Q24.1. Reason: When a bar magnet is brought near the center of another bar magnet as shown in Figure Q24.1, the force between the bar magnets is zero. The attractive force between the bar magnets' north-south sides cancels the repulsive force between the bar magnets' north-north sides.
Assess: If the bar magnet is not exactly in the center, then it will rotate until the two magnets are parallel with north-south and south-north sides touching.

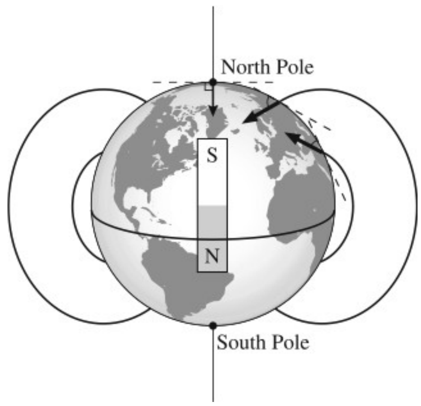
Q24.2. Reason: By tying a string around the center of the bar magnet, one can allow the bar magnet to freely rotate. By suspending the magnet in the earth's atmosphere, the earth's magnetic field will interact with the bar magnet's magnetic field. The interaction between the fields will rotate the bar magnet until it is parallel to the earth's magnetic field, as shown in the figure. Once the bar magnet is parallel to the earth's magnetic field, there will be no net force and the bar magnet will stop rotating. The half of the bar magnet pointing to the geographic north (which is located near the earth's magnetic south pole) will be a north pole whereas the half of the bar magnet pointing to the geographic south direction will be a south pole.



Assess: Anytime a freely suspended bar magnet is in the vicinity of a magnetic field, the magnet will rotate until the two magnets (or magnetic fields) are parallel with north-south and south-north sides touching.

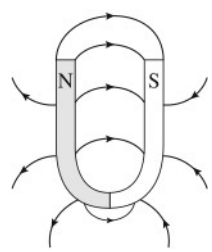
Q24.3. Reason: A compass points near the geographic north because the earth's magnetic field lines run near the geographic South Pole (magnetic north pole) to near the geographic North Pole (magnetic south pole): see Figure 24.8 in textbook. The field is not dependent on the hemisphere one is standing in.
Assess: In a bar magnet magnetic field lines run from a north pole to a south pole. To find the geographic North Pole one uses the north pole of a magnet because the north pole will point in the direction of the earth's magnetic south pole.

Q24.4. Reason: The earth's magnetic field vectors tend to point below the horizon in the northern hemisphere. The angle below the horizon is called the dip angle. But the dip angle changes with latitude. As illustrated in the figure, near the equator, the dip angle is small and near the north pole, the dip angle is nearly 90°. Each different latitude has a certain dip angle and the turtle is able to determine its latitude from the dip angle it senses.



Assess: The way the turtle finds its latitude is similar to the way sailors can find their latitude by looking at the position of stars. For example, a sailor can use the dip angle of the sun's rays at noon to find his or her latitude.

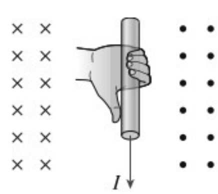
Q24.5. Reason: The figure illustrates the magnetic field lines for a horseshoe magnet.



Assess: Magnetic field lines run from a north pole to a south pole with the arrows showing the direction to and from. The lines should always be equally spaced to show the qualitative strength of the magnetic field.

Q24.6. Reason: Because the north pole of the compass needle points counterclockwise, the magnetic field is counterclockwise. When you curl your right hand fingers counterclockwise, the thumb points out of the page. Thus, the current in the wire is out of the page. This is demonstrated in the opposite direction in Figure 24.11 of the textbook.
Assess: The right hand rule for fields gives the relationship between a current and the circling magnetic field it creates.

Q24.7. Reason: Remember that an "X" represents the magnetic field going into the page. The "dot" is the point of an arrow and illustrates the magnetic field coming out of the page. Curl your right hand's fingers around the wire so that they come out of the page on the right side and into the page on the left side. The direction of your thumb is the direction of the current. Since your thumb now points down, the current in the wire is down: See the figure.



Assess: The right-hand rule for fields gives the relationship between a current and the circling magnetic field it creates.

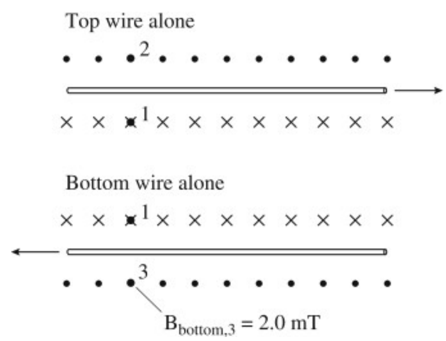
Q24.8. Reason: Conventional household wiring is composed of at least two current-carrying conductors. One conductor carries current to some appliance or light, and another conductor serves as the electrical return. However, household current reverses its direction about 120 times each second, or 60 cycles (reverse and back) each second.

Assess: It is unlikely you could detect current in the walls of a house with a compass for two reasons.
The first reason is if the direction of the current changes 120 times a second, the magnetic field surrounding the current-carrying wire changes direction 120 times each second. The mass inertia of the needle would prevent it from flipping 120 each second.
The second reason a compass would make a poor instrument to find wiring is that since household wiring is composed of a pair of current-carrying conductors close to each other, and the two currents will always be equal in magnitude, yet opposite in direction with each other, their magnetic fields will cancel.

Q24.9. Reason: To find the field at any point, we need to find the field we would have if only the top wire were present and the field we would have if only the bottom wire were present. Let the point where the field is given be called P and let the distance from point P to the bottom wire be called d. At P, the field due to the lower wire is, from the right-hand rule, out of the page. The field at P due to the top wire is into the page. Thus the field strength due to the top wire should be subtracted from the field strength due to the bottom wire (the bottom wire contributes a larger field since point P is closer to the bottom wire):

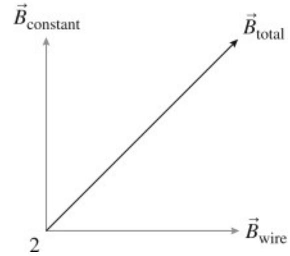
$$B_{\text{total}} = B_{\text{bottom}} - B_{\text{top}} = \frac{\mu_0 I}{2\pi d} - \frac{\mu_0 I}{2\pi(3d)} = \frac{\mu_0 I}{3\pi d}$$

This field is directed out of the page. We know that at point P, $B_{\text{total}} = 2.0\text{ mT} = \dfrac{\mu_0 I}{3\pi d}$, from which it follows that $\dfrac{\mu_0 I}{2\pi d} = 3.0\text{ mT}$. Thus $B_{\text{bottom}} = \dfrac{\mu_0 I}{2\pi d} = 3.0\text{ mT}$. At point 1, the field due to the bottom wire is into the page (from the right-hand rule) and has magnitude $\dfrac{\mu_0 I}{2\pi d} = 3.0\text{ mT}$. Since the top and bottom wires have the same current and are equidistant to point 1, the field at point 1 due to the top wire is also 3.0 mT and from the right-hand rule, is also into the page. Thus the total field at point 1 is 6.0 mT, into the page. Finally, at point 2, the field due to the top wire is $\dfrac{\mu_0 I}{2\pi d} = 3.0\text{ mT}$, out of the page and the field due to the bottom wire is $\dfrac{\mu_0 I}{2\pi(3d)} = \dfrac{3.0\text{ mT}}{3} = 1.0\text{mT}$, into the page. Since the fields are in opposite directions, they are subtracted, as at point P, but now the larger field is out of the page so the total field is out of the page and has magnitude: $3.0\text{ mT} - 1.0\text{ mT} = 2.0\text{ mT}$.



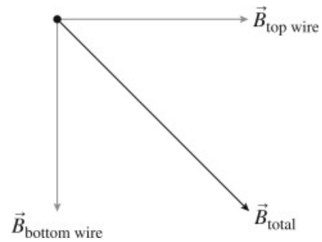
Assess: You might have guessed, using symmetry, that the field at point 2 would be the same as the field at point P. This is because these two points have in common that they are a distance d from one current, I, and a distance $3d$ from an equal current flowing in the opposite direction.

Q24.10. Reason: At point 1, there are two magnetic fields interacting: the uniform magnetic field in the plane of the paper pointing up and the magnetic field from the wire. The way you find the direction of the magnetic field from the current-carrying wire is shown in Section 24.3, using the right-hand rule for fields. The magnetic field from the wire has to be pointing down with the same magnitude as the uniform magnetic field in the plane because the problem states that the total magnetic field is zero at point 1. When the magnetic field from the current is pointing down at point 1, then the magnetic field direction is clockwise around the wire. At point 2, the magnetic field from the current-carrying wire is in the right direction (tangent to the clockwise circular path around the wire). The total magnetic field is therefore the combination of the magnetic field from the wire (to the right) and from the uniform magnetic field (up). The total magnetic field is the resultant vector of the two magnetic field vectors as shown.



Assess: Whenever there are two magnetic fields acting at the same point, you add the fields. If the magnetic fields act in 2-dimensions, then you have the add/subtract them using vector addition. In this case, the vector can be simply drawn as the resultant vector shown.

Q24.11. Reason: Assuming the wire with the current directed to the right is the bottom wire, the bottom current-carrying wire produces a magnetic field pointing toward the bottom of the page at a point halfway between them. The top current-carrying wire produces a magnetic field pointing right at a point halfway between them. The total magnetic field is the resultant vector of the two magnetic fields as shown.



Assess: Whenever there are two magnetic fields acting at the same point, use vector addition to add the fields and find the resultant vector. In this case, the resultant vector is conceptually shown in the previous figure.

Q24.12. Reason: No. Magnetic fields exert a force on moving charges only. The equation for magnetic force, $F = |q|vB\sin\alpha$, shows that if the velocity (v) is zero then the force (F) is zero as well.

Q24.13. Reason: If a current is present in a long solenoid, the magnetic field that is created is uniform along its central axis. The direction of the magnetic field is in the direction the thumb on your right hand points when your fingers are curled in the direction of the current in accordance with the right-hand rule for fields. The magnetic field points to the right. The magnetic field lines shown in Figure 24.17 in the textbook show that the field curves around the *outside* of the solenoid in the other direction. This means the compass needle should point left.
Assess: The right-hand rule can be used to determine the direction of the magnetic field due to any current, even a curved current.

Q24.14. Reason: The magnetic field inside of a solenoid is $B = \mu_0 I \frac{N}{L}$. Note that the magnetic field is independent of the diameter of the solenoid (provided that its length, L, is large in comparison). Therefore, the diameters of the two concentric solenoids do not matter here. In this case, the number of turns, N, and the length, L, is the same for both solenoids. The current, I, is equal, but opposite, between the two solenoids. Therefore:

$$B_{\text{Total}} = B_1 + B_2 = \mu_0 \frac{N}{L}[I_1 + (-I_2)] = 0$$

Assess: The field inside the two solenoids is zero because the current was equal and opposite. Also, the radius of the solenoid does not affect the magnetic field inside for sufficiently long solenoids.

Q24.15. Reason: The direction of the force determines the direction the particle will be deflected when it enters the magnetic field. Use the right-hand rule for forces to determine the direction of the force. **(a)** The velocity points to the right and the magnetic field points into the page so the force points toward the top of the page. **(b)** The velocity points upward and the magnetic field points out of the page. But because the charged particle is negative, the force points to the left.

Assess: The direction of the force on a positive particle is governed by the right-hand rule. Conversely, the force on a negative particle is in the opposite direction of the right-hand rule. For example, if the right-hand rule gives you an up direction, then, for a negative particle, the direction is down.

Q24.16. Reason: The direction of the magnetic force determines the direction that the particle will be deflected when it enters the magnetic field. Use the right-hand rule for forces to determine the direction of the force. See Figure 24.27 in the textbook. **(a)** The velocity points to the right and the magnetic field points toward the bottom of the page, so the force points into the page. **(b)** In this case the velocity and the magnetic field are pointing in the same direction, so there is no force.
Assess: The reason there is no force for part **(b)** can be shown using the equation $F = qvB\sin\alpha$, where α is the angle between the velocity and the magnetic field. So if the velocity is parallel to the magnetic field, this angle is zero, which makes the sine and the force equal zero as well.

Q24.17. Reason: Use the right-hand rule for forces to determine the direction of the magnetic field. See Figure 24.27. **(a)** The velocity points to the right and the force points down, so the magnetic field points out of the page. **(b)** The velocity points to the right and the force points into the page, so the magnetic field should point to the bottom of the page. BUT, because the charged particle is negative, the direction of the magnetic field is opposite. So the field points to the top of the page.
Assess: The direction of the force on a positive particle is governed by the right-hand rule. Conversely, the force on a negative particle is opposite.

Q24.18. Reason: Use the right-hand rule for forces to determine the direction of the magnetic field. For **(a)**, the component of the magnetic field affecting the charged particle points $90°$ clockwise from the direction of the velocity, v is parallel to the plane of the page (note the charge is negative). For (**b**), the component of the magnetic field affecting the charged particle points $90°$ counterclockwise from the direction of the force vector, F, and is parallel to the plane of the page.
Assess: The direction of the magnetic field for a particle is governed by the right-hand rule regardless of what direction the velocity and force are pointing.

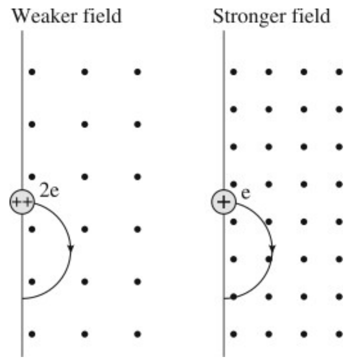
Q24.19. Reason: The direction of the magnetic field of a current-carrying wire is described by the right-hand rule. Using this we see that above the wire the magnetic field is coming out of the page. See Figure 24.30. The force is found by the right-hand rule. For an electron, the force points up.
Assess: Magnetic force depends on charge, velocity, magnetic field, and direction. If you change the sign of the charge the direction of the force is opposite.

Q24.20. Reason: Use the right-hand rule for forces to determine the direction of the magnetic field. When you use the right-hand rule on both particles you get the magnetic field coming out of the page (in the $+x$-direction).
Assess: The fact that the two particles have different directions does not automatically mean they are acted upon by a different magnetic field. In this case the magnetic field is uniform.

Q24.21. Reason: At the earth's magnetic north pole, the field lines come straight up out of the ground, as in the figure. From the right-hand rule, the force on a positive charge placed at point P and moving up the page would be to the right. So the force on an electron would be to the left. Thus the electron is steered to the left and moves counterclockwise, as viewed from above.
Assess: The earth's magnetic north pole is in the southern hemisphere so the revolution of an electron as described in this problem is characteristic of the aurora australis, or southern lights.

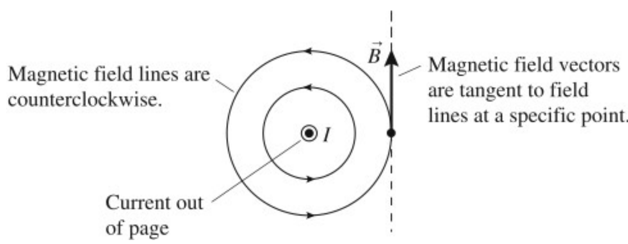
Q24.22. Reason: The dots tell us that the field is out of the page. From the right-hand rule, the force on the proton is to the right, so the proton is steered to the right and its motion is clockwise.
Assess: If the charged particle had been an electron rather than a proton, then the force would have been the opposite of what is predicted by the right-hand rule. The force would have been to the left and the orbit would have been counterclockwise.

Q24.23. Reason: Without using any algebra, we can reason that an ion with more charge will experience a greater force (and therefore be steered around a smaller circle) if the same magnetic field is used. Since the two groups of ions landed at the same spot, we can conclude that the one with the charge advantage, that is, the ion with charge $2e$, must have been steered by a weaker electric field. Thus peak A corresponds to the ions with charge $2e$ and peak B corresponds to the ions with charge e. Another way to consider this question is to solve Equation 24.8 for the charge of an ion revolving in a magnetic field. Doing so, we obtain: $|q| = \frac{(mv/r)}{B}$. The two groups of ions have the same mass, velocity and orbital radius, so they have the same numerator. It follows that peak B, which is at a higher field will correspond to ions with a lower charge, that is, those of charge e.



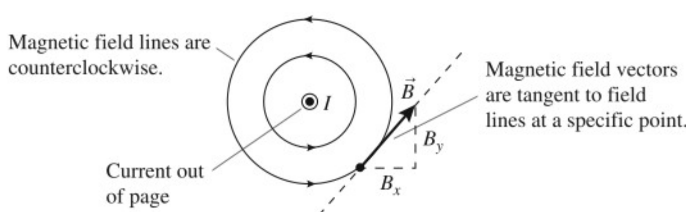
Assess: The minimum charge a positive ion can have is $+e$, and the next smallest value is $+2e$, so if it turns out that there are more than two different charge values among these ions (more than just $+e$ and $+2e$), those ions would have greater charge and so the peaks associated with them would be to the left of peak A.

Q24.24. Reason: The way you find the direction of the magnetic field from a current-carrying wire is shown in Section 24.3, using the right-hand rule for fields. The magnetic field for a current coming out of the page is curling around the wire in the counterclockwise direction.



Because the magnetic field at the proton is parallel to the velocity of the proton, the force on the proton is zero.
Assess: Whenever the magnetic field and the velocity are parallel to each other the force is always zero. As seen by $F = qvB\sin\alpha$, where α is the angle between the velocity and the magnetic field. If α is 0, then $F = 0$.

Q24.25. Reason: The way you find the direction of the magnetic field from a current carrying wire is shown in Section 24.3, using the right-hand rule for fields. The magnetic field for a current coming out of the page is curling around the wire in the counterclockwise direction.



The magnetic field vector can be split into two components, B_x and B_y. The component that is parallel to the velocity (B_y) contributes no force, because α is zero in the magnetic force equation $F = qvB\sin\alpha$. The component of the magnetic force that is perpendicular to the velocity (B_x) contributes a force, and by the right-hand rule for forces, the force is pointing into the page.
Assess: Even though the magnetic field was not in a convenient direction, only the component that is perpendicular to the velocity exerts a force on the particle.

Q24.26. Reason: The direction of the straight wire current is up. At the location of the square loop, the current in the straight wire generates a magnetic field that is into the page.
We can disregard the forces created by current within the top and bottom sides of the square, since they both run perpendicular to the straight wire, and are equal distance from the wire. The forces from the top and bottom sides conveniently cancel each other out.
However, the forces from the two sides of the square loop that run parallel to the straight wire (the left and right sides) do not cancel each other out. The magnetic force from the side of the square loop that is on the left (closest to the straight wire) will be stronger than the magnetic force felt on the right side (furthest from the straight wire) of the square loop. The current on the left side of the square loop is opposite from the current in the wire, therefore, the wires will repel each other. There will be an attractive force from the right side current, but this effect is less than the other side since it is twice as far away. The parallel sides do not cancel each other out. Therefore, the net force on the square loop is to right, or positive *x* direction.
Will there be any torque on the loop? No. The current in the square loop generates a magnetic dipole, and the current direction in the square loop is such that the dipole moment is aligned with the magnetic field from the straight wire.
Assess: When current carrying wires are parallel, they experience an attractive force when the currents are in the same direction and a repulsive force when the currents are in the opposite direction.

Q24.27. Reason: The high magnetic field produced by the MRI would alter the path of the electrons in the cathode ray tube. The CRT monitor would only display an extremely distorted image, much like what would happen to a television in the presence of a strong magnetic field.
Assess: Magnetic fields exert a force on moving charges.

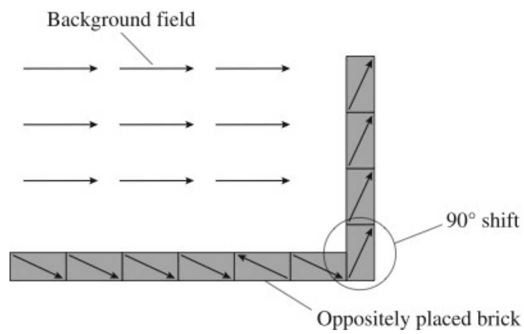
Q24.28. Reason: Once the slinky is stretched out and a current is passed through it, the separate coils act as current loops. The current flows through each loop in the same direction so they will attract each other causing the slinky to contract.
Assess: When current flows around two current loops (or two parallel wires) in the same direction they are attracted to each other. This attraction causes the slinky to contract.

Q24.29. Reason: The force a magnetic field exerts on a current-carrying wire is given by Equation 24.14: $F_{\text{wire}} = ILB\sin\alpha$. In a solenoid the magnetic field inside runs parallel to the axis. If the wire runs down the middle of the solenoid then $\alpha = 0$ and $\sin 0 = 0$ so there is no force on the wire due to the field of the solenoid.
Assess: This situation could also be analyzed by looking at the moving charges in the wire and applying Equation 24.5.

Q24.30. Reason: To make an electromagnet, you should use wire covered in plastic. This way, the current cannot leak from one turn of the wire to an adjacent turn. To get a strong field in a solenoid, you want the current to move through the solenoid in a helical path. But if adjacent turns of wire are not insulated, then the current can go directly from one turn to the next without having to go around the solenoid. In addition, since a nail is used, which has a large diameter and therefore a low resistance, much of the current will actually travel through the nail, from the point where the solenoid starts to the point where it ends.
Assess: If we used bare wire, there would still be an electric current and, consequently, a magnetic field. But insulation guides the current through the optimal helical path, increasing the magnetic field strength.

Q24.31. Reason: The moon contains rocks that were magnetized, and in fact some parts of the moon's surface are magnetized. One theory suggests that the moon at one time had a molten core, and when the outer surface of the Moon cooled, the magnetic field of the molten core aligned the atoms of the metallic elements on the moon's surface. Since the surface of the moon has not been disturbed or heated, the ferromagnetic material continued to keep the alignment of the atoms, and therefore stayed magnetized.
Assess: One theory why the earth is magnetized suggests that the earth's molten core cycles the metal core through convection and moves the charged particles with it. This cyclic motion, like any circular electric current, creates a dipole magnetic field. This earth's magnetic field over time magnetizes any ferromagnetic material on earth (i.e., by aligning the dipole moments in the atoms).

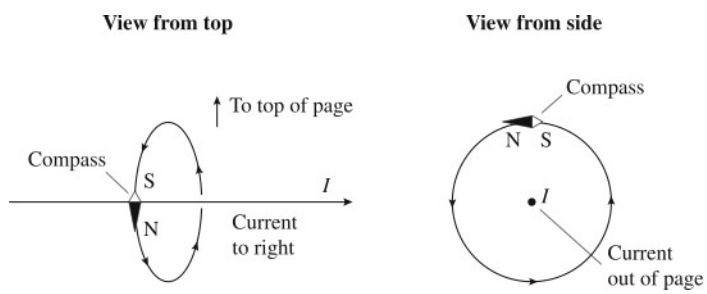
Q24.32. Reason: After the bricks cool off, their magnetic field is parallel to that of the earth. They are then laid in the wall and are likely reoriented in the process. For example, the bricks might be fired with their long side lined up east-west and then placed in a wall where their long side is oriented north-south. There is a good chance that many of the bricks used have the same angle between their magnetic field and their long axis. These ideas could be used by an archaeologist to detect a brick structure. In a background of rock with magnetic field vectors all pointing in the same direction (this would be remnants of all the stuff in their dwelling which was not fired), the archaeologist might detect a narrow region in which the magnetic field vectors point in different directions from the background field. This narrow region would be the wall. The archaeologist might also be able to detect the locations where two walls join at a right angle. Where two walls join, the orientation of the bricks is shifted by 90°. It follows that the orientation of the magnetic field vectors would shift at a joint in the building. Or if a brick were for some reason laid on the wall "backward" relative to the surrounding bricks, that brick could be identified. These ideas are illustrated in the figure.



Assess: Simply by measuring the magnetic field at multiple places in an archaeological site, the scientist can not only locate the presence of man-made structures, but he can also identify individual bricks and features of the building.

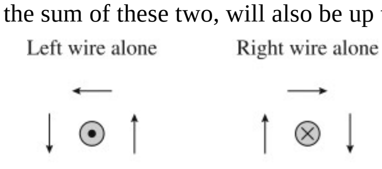
Q24.33. Reason: While the metal sphere must be made of a magnetic material in order to experience the strong attraction to the magnet, it is likely not a magnet itself. So it would be equally attracted to the south pole of the bar magnet. The correct choice is A.
Assess: A metal object made of a magnetic material but which is not a permanent magnet will be attracted to both ends of a magnet. Try this at home with a magnet and some paper clips.

Q24.34. Reason: A magnetic field points counterclockwise around the wire using the right-hand rule for current-carrying wires. Viewed from the top, the magnetic field circles out of the page above the wire and into the page below the wire. This means above the wire the north pole should face toward the bottom of the page.



The correct choice is C.
Assess: Choices B and D are incorrect because the compass points along the direction of the current wire and the magnetic field from a current-carrying wire circles around the wire. Choice A is incorrect because the compass points north below the wire. Choice C is correct because the compass points north above the wire.

Q24.35. Reason: Using the right-hand rule for fields, we conclude that the field at the point in question, due to the wire on the left is directed up the page. The field due to the wire on the right is also up the page at the midpoint. So the total field, which is the sum of these two, will also be up the page. The answer is A.



Assess: The orientation of the currents was very important here. For example, if both currents had been directed out of the page, then the field due to the wire on the left would still be up the page, but the field due to the wire on the right would be down the page. The total field would be zero.

Q24.36. Reason: When a charged particle enters a uniform magnetic field it moves in uniform circular motion. The radius of the curvature is given by $r = mv/(qB)$. The correct choice is D.

Assess: Since path D has the largest circular radius, it has the largest mass. The problem stated that the particles have the same speed (v), same charge (q), and enter the same uniform magnetic field (B).

Q24.37. Reason: When a charged particle enters a uniform magnetic field it moves in uniform circular motion. The radius of the curvature is determined by $r = mv/(qB)$, so the larger the radius, the larger the velocity. From the choices given, D has the largest radius, so it also has the highest velocity. The correct choice is D.

Q24.38. Reason: By the right-hand rule for fields, if these were protons, the magnetic field would be out of the plane of the paper. But because the particles are electrons, the field must point into the plane of the paper to get the desired deflection. Therefore the answer is D.
Assess: The direction determined by the right-hand rule assumes a positive change, so for a negative charge the results must be reversed.

Q24.39. Reason: The answer is C because magnets want to line up north to south. In answers A and D, the same pole was facing each other so they would repel. In answer B, the compasses are free to rotate, and would not assume this configuration if they could move.

Problems

P24.1. Prepare: Table 24.1 in the textbook shows magnetic field strengths. The equation for a magnetic field due to a long straight wire is $B = \mu_0 I/(2\pi R)$.

Solve: In this problem $R = 1.0\text{ cm} = 0.01\text{ m}$, so the previous equation can be rewritten to solve for current, $I = 0.02\pi B/\mu_0$

$$I_{\text{earth surface}} = \frac{0.02\pi 5\times 10^{-5}}{\mu_0} = 2.5\text{ A}$$

$$I_{\text{refrigerator}} = \frac{0.02\pi 5\times 10^{-3}}{\mu_0} = 250\text{ A}$$

$$I_{\text{laboratory}} = \frac{0.02\pi(0.1-1)}{\mu_0} = 5000-50{,}000\text{ A}$$

$$I_{\text{magnet}} = \frac{0.02\pi 10}{\mu_0} = 500{,}000\text{ A}$$

Assess: As one would expect, high current is needed to produce a high magnetic field.

P24.2. Prepare: Table 24.1 shows magnetic field strengths as shown in Problem 1. The equation for a magnetic field due to a long straight wire is $B = \mu_0 I/(2\pi R)$.

Solve: In this problem $I = 10$ A so the previous equation can be rewritten to solve for distance: $R = \mu_0 I/(2\pi B)$.

$$R_{\text{earth surface}} = \frac{10\mu_0}{2\pi 5\times 10^{-5}} = 4.0\text{ cm}$$

Solving, likewise, we get the distances of the refrigerator magnet, the laboratory magnet, and the superconducting magnet to be 0.4 mm, 20 μm to 2 μm, and 0.20 μm, respectively.
Assess: As we would expect, magnetic field strength decreases as we move away from the current-carrying wire.

P24.3. Prepare: The equations for the magnetic field at the center of a loop and a wire are

$$B_{\text{loop center}} = \mu_0 I/(2R) \quad \text{and} \quad B_{\text{wire}} = \mu_0 I/(2\pi R)$$

Solve: **(a)** The radius of the loop is 0.5 cm and the magnetic field is 2.5 mT so the current is:

$$B_{\text{loop center}} = \frac{\mu_0 I}{2R} \Rightarrow I = \frac{2RB_{\text{loop center}}}{\mu_0} = \frac{2(0.5\times10^{-2}\text{ m})(2.5\times10^{-3}\text{ T})}{4\pi(10^{-7}\text{ T}\cdot\text{m/A})} = 19.89\text{ A}$$

which will be reported as 20 A.
(b) For a long, straight wire that carries a current I, the magnetic field strength is

$$B_{\text{wire}} = \frac{\mu_0 I}{2\pi d} \Rightarrow 2.50\times10^{-3}\text{ T} = \frac{4\pi(10^{-7}\text{ T}\cdot\text{m/A})(19.89\text{ A})}{2\pi d} \Rightarrow d = 1.6\times10^{-3}\text{ m}$$

Assess: The result for d obtained is consistent with the equations for B_{wire} and $B_{\text{loop center}}$.

P24.4. Prepare: From Table 24.1 the earth magnetic field is equal to 5×10^{-5} T and the magnetic field at the center of a current loop $B = \mu_0 NI/(2R)$.
Solve: Rearranging the equation for a current loop the current would be

$$I = \frac{2RB}{\mu_0 N} = \frac{2(0.50\text{ m})(5\times10^{-5}\text{ T})}{4\pi(10^{-7}\text{ T}\cdot\text{m/A})(200)} = 0.2\text{ A}$$

Assess: We expected a small current through the loop because earth's magnetic field strength is weak.

P24.5. Prepare: Assume the wires are infinitely long. Find the contribution of the magnetic field due to each wire.
Solve: The magnetic field strength at point 1 is

$$\vec{B}_1 = \vec{B}_{\text{top}} + \vec{B}_{\text{bottom}} = \left(\frac{\mu_0 I}{2\pi d}, \text{ out of page}\right)_{\text{top}} + \left(\frac{\mu_0 I}{2\pi d}, \text{ into page}\right)_{\text{bottom}}$$

$$B_1 = \frac{\mu_0 I}{2\pi}\left(\frac{1}{2\text{ cm}} - \frac{1}{(4+2)\text{ cm}}\right) = (2)(10^{-7}\text{ T}\cdot\text{m/A})(10\text{ A})\left(\frac{1}{2\times10^{-2}\text{ m}} - \frac{1}{6\times10^{-2}\text{ m}}\right)$$

$$\vec{B}_1 = (6.7\times10^{-5}\text{ T, out of page})$$

At points 2 and 3,

$$\vec{B}_2 = \left(\frac{\mu_0 I}{2\pi(2\text{ cm})}, \text{ into page}\right) + \left(\frac{\mu_0 I}{2\pi(2\text{ cm})}, \text{ into page}\right) = (2.0\times10^{-4}\text{ T, into page})$$

$$\vec{B}_3 = \left(\frac{\mu_0 I}{2\pi(6\text{ cm})}, \text{ into page}\right) + \left(\frac{\mu_0 I}{2\pi(2\text{ cm})}, \text{ out of page}\right) = (6.7\times10^{-5}\text{ T, out of page})$$

Assess: Each point is affected by both wires, so the contributions must add according to the direction of the field points. The equation of the magnetic field does not give its direction, only its magnitude. To get the direction you must use the right-hand rule. If the fields are in the same direction, they add. If they are in different directions, they subtract.

P24.6. Prepare: Use the equation for the magnetic field for a long straight wire.
Solve: **(a)** The field of a transmission line is around

$$B = \frac{\mu_0}{2\pi}\frac{I}{d} = \frac{(2\times10^{-7}\text{ T}\cdot\text{m/A})(200\text{ A})}{20\text{ m}} = 2.0\times10^{-6}\text{ T} = 2.0\ \mu\text{T}$$

(b) The earth's field is $B_{\text{earth}} = 5\times10^{-5}\text{ T} = 50\ \mu\text{T}$, so $B_{\text{wire}}/B_{\text{earth}} = 2.0\ \mu\text{T}/(50\ \mu\text{T}) = 0.04 = 4.0\%$.
Assess: The field produced by a transmission line on the ground is much smaller than the earth's magnetic field.

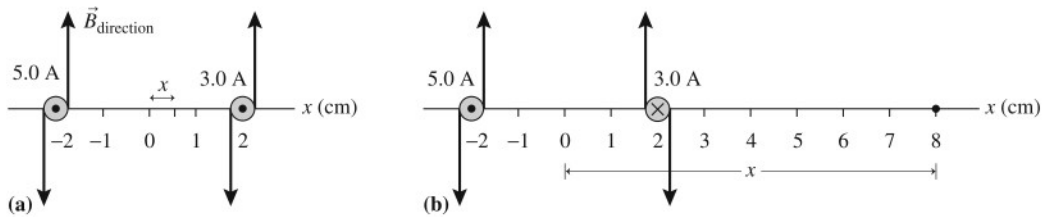
P24.7. Prepare: We need the formula for the magnetic field of a straight wire.
Solve: **(a)** Let's estimate that the baby is 10 cm (≈ 4 inches) from a 1 A current. Here the magnetic field is

$$B = \frac{\mu_0}{2\pi}\frac{I}{d} = \frac{(2\times10^{-7}\text{ T}\cdot\text{m/A})(1\text{ A})}{0.1\text{ m}} = 2.0\times10^{-6}\text{ T} = 2.0\ \mu\text{T}$$

(b) The two magnetic fields produced will be in opposite directions so they will cancel each other out.

Assess: The magnetic field produced by an electric blanket on a baby, even if the wires are not oppositely paired, is much smaller than the earth's magnetic field.

P24.8. Prepare: When calculating the magnetic field at a point, you need to use the right-hand rule for magnetic fields as well as set up a good coordinate system (origin is between the two wires). The magnetic fields' direction on the *x*-axis for part **(a)** and **(b)** will depend on the side of the wire: See figure.



In part **(a)**, between the two wires, the magnetic field will be up for the 5.0 A current and down for the 3.0 A current. Outside the two wires ($x < -2$, $x > 2$), the magnetic field will be in the same direction. In part **(b)**, between the two wires, the magnetic field will be in the same direction (up). Outside the two wires, the magnetic field will be opposite. The magnetic field will be zero when the two magnetic fields cancel.

Solve: **(a)** The point where the two magnetic fields cancel lies on the *x*-axis in between the two wires. Let that point be a distance *x* away from the origin. Because the magnetic field of a long wire is $B = \mu_0 I/(2\pi r)$ and the fields cancel when $B_{5.0\text{ A}} = B_{3.0\text{ A}}$, we have

$$\frac{\mu_0(5.0\text{ A})}{2\pi(0.02\text{ m}+x)} = \frac{\mu_0(3.0\text{ A})}{2\pi(0.02\text{ m}-x)} \Rightarrow 5(0.02\text{ m}-x) = 3(0.02\text{ m}+x) \Rightarrow x = 0.005\text{ m} = 0.50\text{ cm}$$

(b) The magnetic fields due to the currents in the two wires add in the region −2.0 cm < *x* < 2.0 cm. For *x* <–2.0 cm, the magnetic fields subtract, but the field due to the 5.0 A current is always larger than the field due to the 3.0 A current. However, for *x* > 2.0 m, the two fields will cancel at a point on the *x*-axis. Let that point be a distance *x* away from the origin, so

$$\frac{\mu_0(5.0\text{ A})}{2\pi(x+0.02\text{ m})} = \frac{\mu_0(3.0\text{ A})}{2\pi(x-0.02\text{ m})} \Rightarrow 5(x-0.02\text{ m}) = 3(x+0.02\text{ m}) \Rightarrow x = 0.08\text{ m} = 8.0\text{ cm}$$

Assess: The values of *x* obtained seem reasonable.

P24.9. Prepare: Assume that the superconducting niobium wire is very long.
Solve: The magnetic field of a long wire carrying current *I* is

$$B_{\text{wire}} = \frac{\mu_0 I}{2\pi r}$$

We're interested in the magnetic field of the current right at the surface of the wire, where $r = 1.5\text{ mm} = 1.5\times 10^{-3}\text{m}$. The maximum field is 0.10 T, so the maximum current is

$$I = \frac{(2\pi r)B_{\text{wire}}}{\mu_0} = \frac{2\pi(1.5\times10^{-3}\text{ m})(0.10\text{ T})}{4\pi\times10^{-7}\text{ T}\cdot\text{m/A}} = 750\text{ A}$$

Assess: The current density in this superconducting wire is of the order of $1\times10^8\text{ A/m}^2$ (or current/area $= 750\text{ A}/(\pi(1.5\times10^{-3})^2\text{ m}^2) \cong 1.06\times10^8\text{ A/m}^2$). This is a typical value for conventional superconducting materials.

P24.10. Prepare: We use the formula for the magnetic field due to a long straight wire: $B = \dfrac{\mu_0 I}{2\pi r}$.

Solve: Plugging in the current and distance yields:

$$B = \frac{\mu_0 I}{2\pi r} = \frac{(4\pi \times 10^{-7}\ \text{T}\cdot\text{m/A})(4.0\times 10^{-8}\ \text{A})}{2\pi(1.0\times 10^{-3}\ \text{m})} = 8.0\times 10^{-12}\ \text{T}$$

Assess: This is a very small field—smaller than earth's by seven orders of magnitude. However, this result is not surprising if we compare it to problem 1 in which a current of $2.5\ \text{A}$ was needed to make a field equal to the earth's at a distance of $1.0\ \text{cm}$. At $1.0\ \text{mm}$, only one quarter of an amp would be needed. But the current in this problem is much smaller than $0.25\ \text{A}$.

P24.11. Prepare: The magnetic field in the center of a solenoid is $B = \mu_0 I\, N/L$. This equation is independent of the radius of the solenoid, and therefore only depends on the current (I), number of loops (N), and the length of the solenoid (L).
Solve: Rewriting the equation for a solenoid, one can calculate the current in the wire to be the following:

$$B = \frac{\mu_0 IN}{L} \Rightarrow I = \frac{BL}{\mu_0 N}$$
$$I = \frac{(1.0\ \text{T})(2\ \text{m})}{(4\pi\times 10^{-7}\ \text{T}\cdot\text{m/A})(1000)} = 1.6\times 10^{3}\ \text{A} = 1.6\ \text{kA}$$

Assess: This current is very high. It is about 1000 times greater than a normal electrical current.

P24.12. Prepare: The magnetic field at the center of the two loops is zero, so the magnetic field of the inner loop must be equal and opposite to the magnetic field of the outer loop.
Solve:

$$B_{\text{inner}} = \frac{\mu_0(12\ \text{A})}{2(0.03\ \text{m})} = 2.51\times 10^{-4}\ \text{T}$$
$$B_{\text{center}} = B_{\text{outer}} + B_{\text{inner}} = 0$$
$$B_{\text{outer}} = \frac{\mu_0(-20\ \text{A})}{2R} = -2.51\times 10^{-4}\ \text{T}$$
$$R = 0.05\ \text{m} = 5\ \text{cm}$$

Assess: For the magnetic field at the center of the two loops to be zero, the two magnetic fields must be equal and opposite. The current in the outer loop is assumed to be in the negative direction because it is the only variable that can be negative. A negative radius has no physical meaning.

P24.13. Prepare: If we model the current as a single (N = 1) circular current loop we will want to use Equation 24.2.

$$B = \frac{\mu_0 I}{2R}$$

We are given $B = 3.0\times 10^{-12}$ T and $R = 0.080$ m; we are asked to find I.
Solve: Solve for I.

$$I = \frac{2RB}{\mu_0} = \frac{2(0.080\ \text{m})(3.0\times 10^{-12}\ \text{T})}{4\pi\times 10^{-7}\ \text{T}\cdot\text{m/A}} = 3.8\times 10^{-7}\ \text{A}$$

Assess: This is a small current, but it seems reasonable for a current in one's head. After all, the magnetic field produced is also very small.
Notice the units; both m and T cancel to leave A.

P24.14. Prepare: From Table 24.1, the magnetic field of the earth is $5\times 10^{-5}\ \text{T}$. The magnetic field in the center of a solenoid is $B = \mu_0 IN/L$. This equation is independent of the radius of the solenoid, and therefore only depends on the current (I), number of loops (N), and the length of the solenoid (L).

Solve: Rewriting the equation for a solenoid, one can calculate the current in the wire to be the following:

$$B = \frac{\mu_0 IN}{L} \Rightarrow I = \frac{BL}{\mu_0 N}$$

$$I = \frac{(5.0\times10^{-5}\,\text{T})(4.0\text{ m})}{(4\pi\times10^{-7}\,\text{T}\cdot\text{m/A})(5000)} = 31.8\times10^{-3}\,\text{A} = 32\text{ mA}$$

Assess: The magnetic field of the earth can be cancelled by using a solenoid with relatively little current.

P24.15. Prepare: This problem can be envisioned as a superposition of a straight current and a current loop. The magnetic field at the center of a loop is the combination of both the magnetic field of the loop plus the magnetic field of the straight part of the wire.

$$B_{\text{loop}} = \mu_0 I/(2R) \quad \text{and} \quad B_{\text{wire}} = \mu_0 I/(2\pi r)$$
$$\vec{B}_{\text{total}} = \vec{B}_{\text{loop}} + \vec{B}_{\text{wire}}$$

Note that for the magnetic field of the loop, R is the radius of the loop, whereas, for the magnetic field of the wire, r is the distance from the straight section of the wire. In this situation, r is the distance from the point where the wire begins to bend into a loop. By using the right-hand rule, we see the directions of both magnetic fields point in the same direction, down. Therefore, the two magnetic fields add together.

Solve: The magnetic field at the center of the loop is:

$$\begin{aligned}B_{\text{total}} &= \frac{\mu_0 I}{2R} + \frac{\mu_0 I}{2\pi r} = \frac{\mu_0 I}{2}\left[\frac{1}{R} + \frac{1}{\pi r}\right]\\ &= \frac{(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A})(5.0\text{ A})}{2}\left[\frac{1}{0.01\,\text{m}} + \frac{1}{\pi(0.01\,\text{m})}\right]\\ &= 4.1\times10^{-4}\,\text{T}\end{aligned}$$

Assess: Since magnetic fields are vector fields, we can use superposition.

P24.16. Prepare: We are not given the length of this coil, so we assume the 100 turns are all close together and we treat it as an N-turn coil rather than a solenoid. The applicable equation is Equation 24.3.
We are given $N = 100$, $I = 1.5$ A, and $R = 3.5$ m.

Solve: (a)

$$B = \frac{\mu_0 NI}{2R} = \frac{(4\pi\times10^{-7}\,\text{T}\cdot\text{m/A})(100)(1.5\text{ A})}{2(3.5\,\text{m})} = 2.7\times10^{-5}\,\text{T}$$

(b) Table 24.1 indicates that the field strength at the surface of the earth is about 5×10^{-5} T, and our answer is smaller than that by about half.

Assess: The sharks are detecting a field strength that is about half as strong as the earth's field. They can, therefore, presumably detect the earth's field. Some other species may also be sensitive to magnetic fields.

P24.17. Prepare: The heart is compared to a loop of current with radius 6 cm and magnetic field of 90 pT at its center.

Solve: The current needed to produce this field can be computed from the equation for a magnetic field at the center of a loop.

$$I = \frac{2BR}{\mu_0} = \frac{2(90\times10^{-12}\,\text{T})(0.06\text{ m})}{(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A})} = 8.6\times10^{-6}\,\text{A}$$

Assess: This is a small current, as we would have expected.

P24.18. Prepare: The magnetic field for a current loop wire is different from the magnetic field of an ideal solenoid: $B_{\text{current loop at center}} = \mu_0 NI/(2R)$. This equation does depend on the radius of the loop (R) as well as the number of loops (N) and current in the wire (I). Since the number of loops was not given in the problem, you have to figure out how many loops can be created based on the radius of a single loop.

Solve: The equation to relate the number of loops to the radius is $N = L/(2\pi r)$. From the current loop equation, the magnetic field at the center of an *N*-turn coil becomes

$$B_{\text{coil center}} = \frac{\mu_0 IN}{2R} = \frac{\mu_0 I}{2R}\left(\frac{L}{2\pi R}\right) = \frac{\mu_0 IL}{2\pi R^2}$$

where we used the requirement that the entire length of wire be used: i.e., $N = L/(2\pi r)$. Solving for *R*,

$$R = \sqrt{\frac{\mu_0}{2}\frac{(1.0\text{ m})I}{2\pi B_{\text{coil center}}}} = \sqrt{\frac{4\pi(10^{-7}\text{ T}\cdot\text{m/A})(1.0\text{ m})(1.0\text{ A})}{4\pi(1.0\times10^{-3}\text{ T})}} = 0.010\text{ m} = 1.0\text{ cm}$$

The diameter of the coil is $D = 2R = 2.0$ cm.

Assess: Using current loops and solenoids, you can engineer experiments to meet your specific needs.

P24.19. Prepare: Assuming the electron is a single particle traveling in a circular orbit, the moving electron is, by definition, a circular current. Any current moving in a circle creates a magnetic field at the center of the orbit.

Solve: The current from a single electron moving in a circular orbit is

$$I = \frac{q}{t} = \frac{qv}{d} = \frac{qv}{2\pi r} = \frac{(1.60\times10^{-19}\text{ C})(2.2\times10^{6}\text{ m/s})}{2\pi(5.3\times10^{-11}\text{ m})} = 1.06\text{ mA}$$

With this current, the magnetic field can be calculated as

$$B = \frac{\mu_0 I}{2r} = \frac{(4\pi\times10^{-7}\text{ T}\cdot\text{m/A})(1.06\times10^{-3}\text{ A})}{2(5.3\times10^{-11}\text{ m})} = 12.5\text{ T}$$

which we'll report as 13 T.

Assess: This is a very large magnetic field strength, but note the extremely small radius of the electron orbit.

P24.20. Prepare: A magnetic field exerts a magnetic force on a moving charge. The magnitude of the magnetic force is calculated using the equation $F_B = |q|\, vB\sin\alpha$. The right-hand rule for forces is used to find the direction.

Solve: **(a)** The magnitude of the magnetic force on the charge is

$$F_B = |q|\, vB\sin\alpha = (1.60\times10^{-19}\text{ C})(1.0\times10^{7}\text{ m/s})(0.50\text{ T})(\sin 45°) = 5.7\times10^{-13}\text{ N}$$

Using the right-hand rule for forces, you find that the direction of the force is in the +*y*-direction or into the page.

(b) Because the magnetic field is parallel to the velocity, the force is zero, $\vec{F}_{\text{on q}} = \vec{0}$ N.

Assess: The direction of the force is consistent with the right-hand rule.

P24.21. Prepare: A magnetic field exerts a magnetic force on a moving charge. The magnitude of the magnetic force is calculated using the equation $F_B = |q|vB\sin\alpha$. The right-hand rule for forces is used to find the direction on a positive charge.

Solve: **(a)** The magnitude of the magnetic force on the charge is

$$F_B = |q|vB\sin\alpha = (1.60\times10^{-19}\text{ C})(1.0\times10^{7}\text{ m/s})(0.50\text{ T})(\sin 90°) = 8.0\times10^{-13}\text{ N}$$

Using the right-hand rule for forces, you find that the direction of the force is in the +*z*-direction or up. So, on the electron the force is in the –*z* direction, or down.

(b) The magnitude of the magnetic force on the charge is

$$F_B = |q|vB\sin\alpha = (1.60\times10^{-19}\text{ C})(1.0\times10^{7}\text{ m/s})(0.50\text{ T})(\sin 90°) = 8.0\times10^{-13}\text{ N}$$

Using the right-hand rule for forces, you find that the direction of the force is in the +*yz*-direction, or 45° up and into the page. So, on the electron the force is 45° down and out of the page.

Assess: The velocity, magnetic field, and magnetic force are always perpendicular to each other. Using the right-hand rule for forces, you can determine the direction of the magnetic force without calculating all the individual components of velocity (*v*) and magnetic field (*B*).

P24.22. **Prepare:** You have a magnetic field of 0.20 T applied to a negative Cl ion with a velocity of 15 cm/s. The angle between the applied magnetic field and the velocity of the ion is assumed to be 90°.
Solve: The magnetic force is given by $F = |q|vB\sin\theta$.

$$F = (1.6\times10^{-19}\ \text{C})(0.15\ \text{m/s})(0.20\ \text{T}) = 4.8\times10^{-21}\ \text{N}$$

Assess: This is a very small force because the ion's speed and charge are small.

P24.23. **Prepare:** Charged particles moving perpendicular to a uniform magnetic field undergo uniform circular motion $(a = v^2/r)$ at a constant speed (v): $F_{\text{net}} = F_{\text{B}} \Rightarrow mv^2/r = qvB$ or $r = vm/(qB)$.
Solve: The calculations for the radius of the circular orbit is

$$r_{\text{electron}} = \frac{vm}{qB} = \frac{(1.0\times10^{6}\ \text{m/s})(9.11\times10^{-31}\ \text{kg})}{(1.60\times10^{-19}\ \text{C})(5\times10^{-5}\ \text{T})} = 1.14\times10^{-1}\ \text{m} = 11.4\ \text{cm}$$

$$r_{\text{proton}} = \frac{vm}{qB} = \frac{(5.0\times10^{4}\ \text{m/s})(1.67\times10^{-27}\ \text{kg})}{(1.60\times10^{-19}\ \text{C})(5\times10^{-5}\ \text{T})} = 10.4\ \text{m}$$

Assess: In a magnetron, the charged particles have an angular velocity related to the linear velocity by $v = \omega r = 2\pi fr$, where f is the frequency and r is the radius of the circular motion. These charged particles create light that can be seen at the North Pole and South Pole, and the patterns are from these orbits.

P24.24. **Prepare:** The frequency of the circular orbit can be calculated from angular frequency, $\omega = 2\pi f = v/r$, and the radius, $r = vm/(qB)$.
Solve:

$$r = v/(2\pi f) \quad \text{and} \quad r = vm/(qB)$$

$$\frac{v}{2\pi f} = \frac{vm}{qB} \Rightarrow f = \frac{qB}{2\pi m}$$

$$f_{\text{electron}} = \frac{(1.60\times10^{-19}\ \text{C})(5.0\times10^{-5}\ \text{T})}{2\pi(9.11\times10^{-31}\ \text{kg})} = 1.4\times10^{6}\ \text{Hz}$$

$$f_{\text{proton}} = \frac{(1.60\times10^{-19}\ \text{C})(5.0\times10^{-5}\ \text{T})}{2\pi(1.67\times10^{-27}\ \text{kg})} = 760\ \text{Hz}$$

Assess: These are rather high frequencies. The proton's frequency is higher because of its higher mass.

P24.25. **Prepare:** Carefully examine Example 24.5 as a lead-in to this problem. Instead of the time (period) for one orbit we want the frequency, and $f = 1/T$.

$$f = \frac{|q|B}{2\pi m}$$

We are given $f = 2.4\ \text{GHz}$, and we look up the mass of the electron: $m = 9.11\times10^{-31}\ \text{kg}$.
Solve: Solve the equation for B.

$$B = \frac{2\pi mf}{|q|} = \frac{2\pi(9.11\times10^{-31}\ \text{kg})(2.4\ \text{GHz})}{1.6\times10^{-19}\ \text{C}} = 0.086\ \text{T}$$

Assess: The emitted electromagnetic waves have a wavelength of 12.5 cm and are just right to excite the water molecules and cook the food.

Check the units. $1\ \text{C} = 1\ \text{A}\cdot\text{s}$ and $1\ \text{Hz} = 1\ \text{s}^{-1}$, so the units combine to give T (see Example 24.7).

P24.26. **Prepare:** Charged ions in a mass spectrometer move in circular orbits in a uniform magnetic field. Refer to figure 24.38. Equation 24.8 governs the motion of ions in a mass spectrometer.
Solve: The problem states that the ion has one electron removed, so the net charge on the ion is positive, and equal to the charge of a proton, so $q = 1.6\times10^{-19}\ \text{C}$. The total mass of the ion is 85 times the mass of the proton, so $m = 85(1.67\times10^{-27}\ \text{kg}) = 1.42\times10^{-25}\ \text{kg}$.

Solving Equation 24.8 for R:

$$R = \frac{mv}{qB} = \frac{(1.42\times10^{-25}\text{ kg})(2.3\times10^{5}\text{ m/s})}{(1.6\times10^{-19}\text{ C})(0.80\text{ T})} = 2.6\times10^{-1}\text{ m}$$

The distance between where the ion enters and exits the field is $2R = 5.2\times10^{-1}\text{ m}$.

P24.27. Prepare: Determining the mass of the particle will be useful in determining the type of particle. A mass spectrometer is used to determine the mass of ions or charged particles. The mass of a particle measured by a mass spectrometer is given by Equation 24.8.
Solve: Using Equation 24.8:

$$m = \frac{qBR}{v} = \frac{(+1.6\times10^{-19}\text{ C})(0.05\text{ T})(0.21\text{ m})}{2.5\times10^{5}\text{ m/s}} = 6.7\times10^{-27}\text{ kg.}$$

This value is a few times the mass of a proton. Assuming the particle is an ion of an element, we can determine the number of proton-mass objects in the nucleus of the element by dividing by the mass of a proton:

$$N = \frac{6.7\times10^{-27}\text{ kg}}{1.67\times10^{-27}\text{ kg}} = 4.$$

A helium atom consists of two protons, two neutrons, and four electrons, which is approximately four times the mass of a proton (neutrons have approximately the same mass of a proton, and the electrons' masses are negligible). Assuming the particle is an ion of an elemental atom, a helium atom with one electron removed matches the properties of the particle.

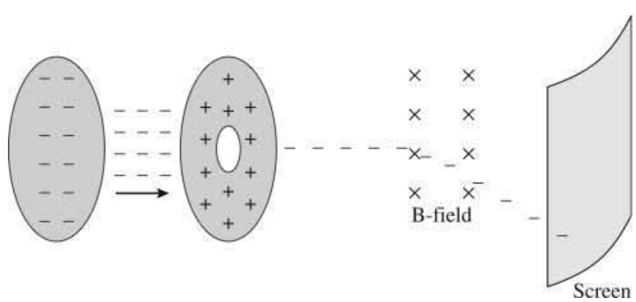
P24.28. Prepare: Using the right-hand rule, you can determine that the magnetic force would point out of the page.
Solve: Therefore, there is no force component from the magnetic field in the *y* or *x* direction.

$$F_z = ma_z = F_B = qvB \Rightarrow a_z = \frac{qvB}{m} \text{ (out of the page)}$$
$$F_y = ma_y = 0 \Rightarrow a_y = 0$$
$$F_x = ma_x = 0 \Rightarrow a_x = 0$$

Thus, the velocity in the *y* direction does not change, because acceleration is zero and the distance the proton moves in the *y* direction is only dependent on the initial velocity in the *y* direction.

$$v_y = v\sin30°$$
$$y = v_y t$$
$$y = (5.5\times10^{5}\text{ m/s})(\sin30°)(10\times10^{-6}\text{ s})$$
$$y = 2.8\text{ m}$$

P24.29. Prepare: The electrons are accelerated by a potential difference, so we need to use the conservation of energy to find their final speed: $\frac{1}{2}mv_i^2 - eV_i = \frac{1}{2}mv_f^2 - eV_f$. Then to find the effect of the magnetic field, we need to use magnetic force law: $F_{mag} = evB$.



Solve: (a) Electrons speed up when they move to higher potential. Let us say that an electron starts at potential 0 V and reaches final speed at potential $3.0\ \text{kV}$. Since the electron also begins with speed 0, its initial energy is 0. The final speed is found as follows:

$$0 = \frac{1}{2}mv_\text{f}^2 - eV_\text{f} \Rightarrow v_\text{f} = \sqrt{\frac{2eV_\text{f}}{m}} = \sqrt{\frac{2(1.60\times10^{-19}\ \text{C})(3.0\times10^{3}\ \text{V})}{(9.11\times10^{-31}\ \text{kg})}} = 3.248\times10^{7}\ \text{m/s},$$

which rounds to $3.2\times10^{7}\ \text{m/s}$,

(b) From Newton's second law,

$$a = \frac{F_\text{mag}}{m} = \frac{ev_\text{f}B}{m} = \frac{(1.60\times10^{-19}\ \text{C})(3.25\times10^{7}\ \text{m/s})(0.65\ \text{T})}{9.11\times10^{-31}\ \text{kg}} = 3.7\times10^{18}\ \text{m/s}^2$$

In terms of g, this is $a = (3.7\times10^{18}\ \text{m/s}^2)\left(\dfrac{g}{9.8\ \text{m/s}^2}\right) = (3.8\times10^{17})g.$

(c) If the electrons were to complete a full orbit, the radius of that orbit would be given by Equation 24.8, $r = \dfrac{mv_\text{f}}{|q|B} = \dfrac{(9.11\times10^{-31}\ \text{kg})(3.25\times10^{7}\ \text{m/s})}{(1.60\times10^{-19}\ \text{C})(0.65\ \text{T})} = 0.28\ \text{mm}$

(d) Magnetic fields apply forces to charged particles in a direction perpendicular to their instantaneous velocity. If we consider a short interval of time, Δt, during which the velocity of the particle is $\vec{v}$, then the particle's displacement is $\vec{v}\Delta t$ while the magnetic force on the particle is perpendicular to that displacement. When force and displacement are always perpendicular, no work is done. By the first law of thermodynamics, if a force does no work on an object, it cannot change the kinetic energy of that object. Thus magnetic fields cannot be used to increase the speed of a charged particle.

Assess: The radius of the electron's orbit worked out in part (c) is very small compared to the size of a television set. Apparently, the magnetic field experienced by an electron is usually much less than $0.65\ \text{T}$, so that the field strength has a time-averaged value much less than $0.65\ \text{T}$.

P24.30. Prepare: Assume that the field is uniform. The wire will float in the magnetic field if the magnetic force on the wire points upward and has a magnitude equal to *mg*, allowing it to balance the downward gravitational force.

Solve: We can use the right-hand rule to determine which field direction makes the wire experience an upward force. The current being from right to left, the force will be up if the magnetic field $\vec{B}$ points out of the page. The forces will balance when $F = ILB = mg$.

$$B = \frac{mg}{IL} = \frac{(2.0\times10^{-3}\,\text{kg})(9.8\,\text{m/s}^2)}{(1.5\,\text{A})(0.10\,\text{m})} = 0.13\,\text{T}$$

Thus $\vec{B}$ = (0.13 T, out of page).

P24.31. Prepare: Two parallel wires carrying currents in opposite directions exert repulsive magnetic forces on each other. Two parallel wires carrying currents in the same direction exert attractive magnetic forces on each other.

Solve: The magnitudes of the various forces between the parallel wires are

$$F_{2\text{ on }1} = \frac{\mu_0 L I_1 I_2}{2\pi d} = \frac{(2\times10^{-7}\ \text{T}\cdot\text{m/A})(0.50\ \text{m})(10\ \text{A})(10\ \text{A})}{0.02\ \text{m}} = 5.0\times10^{-4}\ \text{N} = F_{2\text{ on }3} = F_{3\text{ on }2} = F_{1\text{ on }2}$$

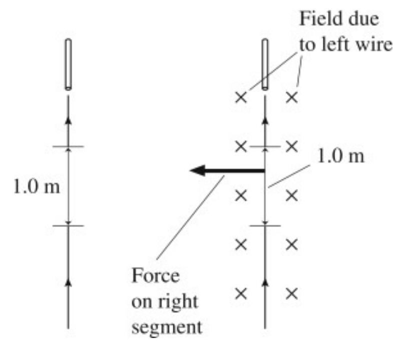
$$F_{3\text{ on }1} = \frac{\mu_0 L I_1 I_3}{2\pi d} = \frac{(2\times10^{-7}\ \text{T}\cdot\text{m/A})(0.50\ \text{m})(10\ \text{A})(10\ \text{A})}{0.04\ \text{m}} = 2.5\times10^{-4}\ \text{N} = F_{1\text{ on }3}$$

Now we can find the net force each wire exerts on the other as follows:

$$\vec{F}_{\text{on 1}} = \vec{F}_{\text{2 on 1}} + \vec{F}_{\text{3 on 1}} = (5.0\times10^{-4}\text{ N, up}) + (-2.5\times10^{-4}\text{ N, down}) = (2.5\times10^{-4}\text{ N, up})$$
$$\vec{F}_{\text{on 2}} = \vec{F}_{\text{1 on 2}} + \vec{F}_{\text{3 on 2}} = (-5.0\times10^{-4}\text{ N, up}) + (+5.0\times10^{-4}\text{ N, down}) = \vec{0}\text{ N}$$
$$\vec{F}_{\text{on 3}} = \vec{F}_{\text{1 on 3}} + \vec{F}_{\text{2 on 3}} = (2.5\times10^{-4}\text{ N, up}) + (-5.0\times10^{-4}\text{ N, down}) = (2.5\times10^{-4}\text{ N, down})$$

Assess: The forces on a wire are cumulative, so the contribution due to the both wires is added.

P24.32. Prepare: To find the force on one of the 1.0 m long segments, we need the formula for the force on a current carrying wire in a magnetic field: $F = BIL.$ The figure shows the field created by the wire on the left and the force felt by the wire on the right. We also need to know the magnetic field experienced by one of the wires (they experience the same field strength). This is given by $B = \dfrac{\mu_0 I}{2\pi r}$.



Solve: Combining the formula for the field experienced by a wire with the formula for the force experienced by the wire gives us the result we want:

$$F = BIL = \left(\frac{\mu_0 I}{2\pi r}\right)IL = \frac{\mu_0 I^2 L}{2\pi r} = \frac{(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A})(1.0\ \text{A})^2(1.0\ \text{m})}{2\pi(1.0\ \text{m})} = 2\times10^{-7}\ \text{N}$$

Assess: This is actually how the amp is defined. You take two long wires and run identical current through them. Then if you gradually vary the current until the force per unit meter on the wires is $2\times10^{-7}\ \text{N/m}$, you know that 1 amp is flowing through the wires. All the units in electricity relate back to the amp. For example, the Coulomb is the amount of charge which flows past a point in a wire in one second if the current in the wire is one amp.

P24.33. Prepare: Assume that the magnetic field is uniform.
Solve: The magnitude of the magnetic force is expressed as $F = ILB\sin\alpha,$ where α is the angle the wire makes with the magnetic field.

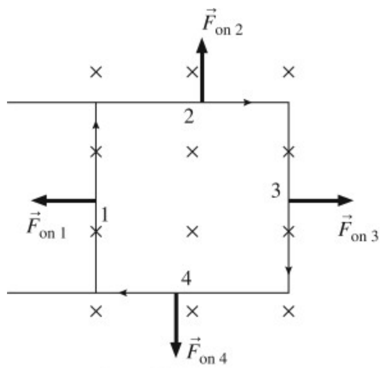
$$F = ILB\sin\alpha$$
$$F = (15\text{ A})(3.0\text{ m})(2.5\text{ T})\ \sin 30°$$
$$F = 56\text{ N}$$

Using the right-hand rule, we can determine that the direction of the force is into the page.
Assess: Given that the current and the magnetic field strength are large, a force of 56 N is reasonable.

P24.34. Prepare: Assume that the magnetic field is uniform.
Solve: The magnitude of the magnetic force is expressed as $F = ILB\sin\alpha,$ where α is the angle the velocity vector makes with the magnetic field.

$$F = ILB\sin\alpha$$
$$100\text{ N} = (15\text{ A})(3.0\text{ m})(2.5\text{ T})\sin\alpha$$
$$\sin\alpha = \frac{100\text{ N}}{(15\text{ A})(3.0\text{ m})(2.5\text{ T})} = \frac{8}{9}$$
$$\alpha = \sin^{-1}\left(\frac{8}{9}\right) = 63°$$

P24.35. Prepare: This problem makes us review some basic concepts in electricity. We will need to find the current in the coil using Ohm's law. Then to find the force on the coil, we will need to use the formula for the force on a current carrying wire: $F = BIL.$ Finally, to find the acceleration of the coil, we will need Newton's second law.



Solve: (a) From Ohm's law we can get the current in the coil:

$$I = \frac{\Delta V}{R} = \frac{5.0\text{ V}}{1.5\ \Omega} = 3.33\text{ A}$$

which rounds to 3.3 A.

(b) Notice in the figure that the four sides of the coil have been numbered 1 through 4. The force on the segments of wire on side 1 is zero because they are not in the magnetic field. The force on the segments on sides 2 and 3 is harder to find because these sides are only partially removed from the field. However, by the right-hand rule for forces, the force on the side 2 segments is up the page, while the force on the side 3 segments is down the page, so the sum of the force on side 2 and the force on side 3 is zero. Consequently, the total force on the coil is merely the force on side 4. The force on a single segment of side 4 is given by:

$$F = BIL = (0.30\text{ T})(3.33\text{ A})(1.0\times10^{-2}\text{ m}) = 1.0\times10^{-2}\text{ N}$$

Side 4 contains 200 such segments so the total force on the coil is $F_{\text{total}} = 200(1.0\times10^{-2}\text{ N}) = 2.0\text{ N}$.

(c) The acceleration of the coil and mount is given from Newton's second law:

$$a = \frac{F_{\text{total}}}{m} = \frac{2.0\text{ N}}{12\times10^{-3}\text{ kg}} = 170\text{ m/s}^2$$

Assess: Note that it is only because side 1 is removed from the magnetic field that there is a net force on the coil. If side 1 were in the region of the field, then the forces on sides 1 and 4 would be equal and opposite and the forces on sides 2 and 3 would be equal and opposite. Thus the total force on the coil would be zero. This is a very large acceleration, but it needs to be in order for the information to be read rapidly off the hard drive.

P24.36. Prepare: If we are given a single loop of current, we know given the magnetic field $B = 0.62$ Tesla, the current I = 240 mA or 0.240 A, the area of the loop A = 0.85 cm^2 or $8.5\times10^{-5}\text{ m}^2$, and applying Equation 24.18, we get the torque on the current loop.

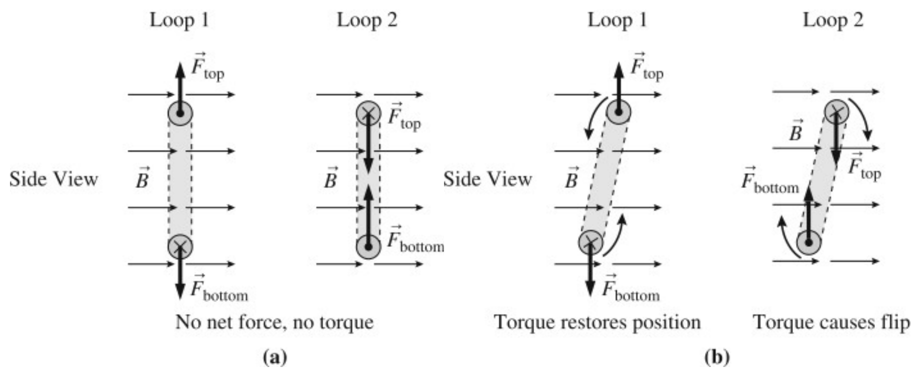
Solve:

$$\tau = (IA)B\sin\theta = (0.24\text{ A})(8.5\times10^{-5}\text{ m}^2)(0.62\text{ T})1$$
$$\tau = 1.26\times10^{-5}\text{ N}\cdot\text{m}$$

P24.37. Solve: From Equation 24.18, the torque on the loop exerted by the magnetic field is

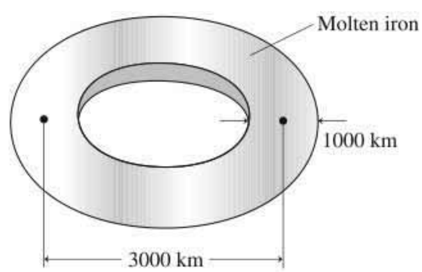
$$\tau = IAB\sin\theta = (0.500\text{ A})(0.05\text{ m}\times 0.05\text{ m})(1.2\text{ T})\sin 30° = 7.5\times 10^{-4}\text{ N}\cdot\text{m}.$$

P24.38. Prepare: The torque on a current loop is due to the magnetic field.



Solve: (a) We can use the right-hand rule to find the force direction on the currents at the top, bottom, front, and back segments of loop 1 and loop 2 in Figure P24.40. We see that $\vec{F}_{top}$ and $\vec{F}_{bottom}$ are equal and opposite to each other. $\vec{F}_{front}$ and $\vec{F}_{back}$ are not seen in the previous figure because they are perpendicular to the page. But, they are also equal and opposite to each other.
Thus, $\vec{F}_{top} + \vec{F}_{bottom} = \vec{0}$ and $\vec{F}_{front} + \vec{F}_{back} = \vec{0}$. Since the top-bottom or front-back forces act along the same line, they cause no torque. Thus, both the loops are in static equilibrium.
(b) Now let us rotate each loop slightly and re-examine the forces. The two forces on loop 1 still give $\vec{F}_{net} = \vec{0}$, but now there is a torque that tends to rotate the left loop *back* to its upright position. This is a restoring torque, so this loop position is stable. But for loop 2, the torque causes the loop to rotate even further. Any small angular displacement gets magnified into a large displacement until the loop gets flipped over. So, the position of loop 2 is unstable.

P24.39. Prepare: A 1000-km-diameter ring makes a loop of diameter 3000 km.



Solve: The current loop has a diameter of 3000 km, so its nominal area, ignoring curvature effects, is

$$A_{loop} = \pi r^2 = \pi(1500\times 10^3\text{ m})^2 = 7.07\times 10^{12}\text{ m}^2$$

Because the magnetic dipole moment of the earth is modeled to be due to a current flowing in such a loop, it is equal to $I\,A_{loop}$. The current in the loop is

$$I = \frac{\text{magnetic dipole moment}}{A_{loop}} = \frac{8.0\times 10^{22}\text{ A}\cdot\text{m}^2}{7.07\times 10^{12}\text{ m}^2} = 1.13\times 10^{10}\text{ A}$$

Assess: Given the large ring diameter and large loop diameter, we expected large current in the loop.

P24.40. Prepare: The wire will create a magnetic field at the position of the loop, so there will be a torque on the loop. The magnetic field created by the wire at the position of the loop will be approximately uniform, since the distance between the wire and the loop is large compared to the size of the loop. It can be approximated by calculating the magnitude and direction of the field created by the wire at the center of the loop. Once this is known, the torque on the loop from this applied field can be calculated. The torque on a loop in a uniform magnetic field is given in Equation 24.18.

Solve: **(a)** The expression for the field created by a wire at the location of the loop is given in Equation 24.1:

$$B = \frac{\mu_0 I}{2\pi r} = \frac{(4\pi \times 10^{-7}\ \text{T}\cdot\text{m/A})(2.0\ \text{A})}{2\pi \times (0.02\ \text{m})} = 2.0 \times 10^{-5}\ \text{T}$$

Using the right-hand rule, the direction of the field will be pointing straight up at the center of the loop, relative to Figure P24.42.

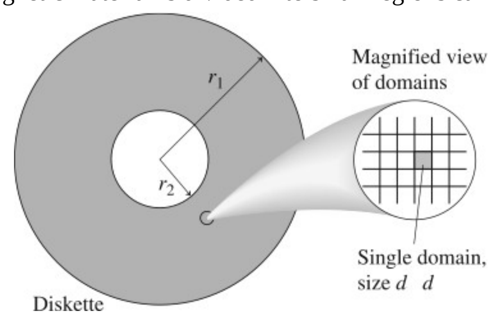
To determine the torque on the loop, we need to determine the angle between this field and the dipole moment of the loop. The dipole moment of the loop points directly left relative to Figure P24.42. So the angle between the applied field and the dipole moment of the loop is $90°$.

Using Equation 24.18:

$$\tau = (IA)B\sin\theta = (0.20\ \text{A})(\pi(0.001\ \text{m})^2)(2.0 \times 10^{-5}\ \text{T})\sin(90^\circ) = 1.3 \times 10^{-11}\ \text{N}\cdot\text{m}$$

(b) The dipole will rotate until the angle between the dipole moment and the field is zero, therefore, it will rotate clockwise $90°$. Once it has rotated to its new position, the angle between the dipole moment and the field will be zero, and the loop will feel no torque or net force. At this point, it will be in equilibrium.

P24.41. **Prepare:** A ferromagnetic material is divided into small regions called magnetic domains.



Solve: A diskette is measured with a ruler and found to have an outer radius $r_1 \approx 4.5$ cm and an inner radius $r_2 \approx 2.0$ cm. The area of one surface is

$$A_{\text{surface}} = \pi\left(r_1^2 - r_2^2\right) \approx 51\ \text{cm}^2 = 5.1 \times 10^{-3}\ \text{m}^2$$

Each side stores ≈500,000 bytes, each of 8 bits. This is N ≈ 4 × 10^6 bits of data. Each bit needs one magnetic domain, so the area of each domain is

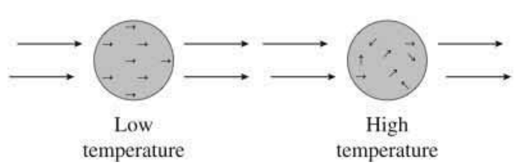
$$A_{\text{bit}} = \frac{A_{\text{surface}}}{N} = \frac{5.1 \times 10^{-3}\ \text{m}^2}{4 \times 10^6} \approx 1.3 \times 10^{-9}\ \text{m}^2$$

If each domain is square and of size $d \times d$, then

$$A_{\text{bit}} = d \times d \Rightarrow\ A_{\text{bit}} = d \times d \Rightarrow d = \sqrt{A_{\text{bit}}} \approx 3.6 \times 10^{-5}\ \text{m} = 0.036\ \text{mm}$$

Assess: Your answer may differ somewhat depending on the assumptions you made, and it will depend on the distance between the domains. This result is consistent with the estimate of 0.1 mm for the size of domains given in Section 24.8.

P24.42. **Prepare:** Picture the situation caused by heating a material. The figure illustrates the dipole's motion at low temperature versus at high temperatures.



Solve: When a group of particles are heated up they tend to move faster. This increase in velocity produces more collision between particles. Well above a certain temperature, particles collide too strongly to maintain an ordered configuration. The same is true for electrons in a ferromagnetic material. Above the Curie temperature the electrons interact so often, and at such a high speed, the material is not able to establish an induced dipole moment.

P24.43. Prepare: For a circuit, voltage = current × resistance ($V = IR$). Also, the current conceptually travels from the positive terminal to the negative terminal.
Solve: (a) When the switch is closed, the current is at a maximum $I = V/R = 5.0/1.0 = 5.0$ A. This current is flowing downward in the wire below the compass, so by the right-hand rule it produces a magnetic field to the left directly above it. The magnitude of the field is:

$$B = \frac{\mu_0 I}{2\pi r} = \frac{(2\times10^{-7}\ \text{T}\cdot\text{m/A})(5.0\ \text{A})}{1.0\times10^{-2}\,\text{m}} = 1.0\times10^{-4}\,\text{T}$$

This is twice the magnetic field of the earth.
(b) The magnetic field due to the earth is 5×10^{-5} T, north, and the magnetic field due to the wire is 1.0×10^{-4} T, west, so the total magnetic field vector is

$$\vec{B}_{\text{total}} = (-1.0\times10^{-4}\ \text{T},\ 5.0\times10^{-5}\ \text{T})$$

where the positive $x-$axis points east and the positive $y-$axis points north. The orientation of this vector is $\theta = \tan^{-1}((1.0\times10^{-4}\ \text{T})/(5.0\times10^{-5}\ \text{T})) = 63^\circ$, counterclockwise from the positive $y-$axis. The compass will rotate until it is 63° counterclockwise from the positive $y-$axis. As time passes, the capacitor discharges and the current in the wire decreases. This means that the $x-$component of the magnetic field approaches zero and as it does, the compass needle approaches the vertical.)

P24.44. Prepare: Assume that the magnetic field is uniform over the 10 cm length of the wire. The force on top and bottom pieces will cancel.
Solve: The current through the 10 cm segment is

$$I = \frac{V}{R} = \frac{15\ \text{V}}{3.0\ \Omega} = 5.0\ \text{A}$$

and is directed down (current is directed from the battery's positive terminal to its negative terminal). The direction of the magnetic force on this wire, given by the right-hand rule for forces, is to the right and perpendicular to both the current and the magnetic field. The magnitude of the force is $F_\text{B} = ILB\sin\alpha = (5.0\ \text{A})(0.10\ \text{m})(50\ \text{mT})\sin(90°) = 0.025\ \text{N}$.

Thus, the magnetic force is $\vec{F} = (0.025\ \text{N, right})$.

P24.45. Prepare: The current in the circuit on the left is I_1 and has a clockwise direction. The current in the circuit on the right is I_2 and has a counterclockwise direction. In the 10 cm section, both currents are traveling down the wire. Two parallel wires carrying currents in the same direction exert attractive magnetic forces on each other.
Solve: The I_1 current through the 10 cm segment is

$$I_1 = \frac{V}{R} = \frac{9.0\ \text{V}}{2.0\ \Omega} = 4.5\ \text{A}$$

The magnitude of the force between them can be used to calculate the current I_2.

$$F_\text{B} = \frac{\mu_0 L I_1 I_2}{2\pi d}$$

$$5.4\times10^{-5}\ \text{N} = \frac{(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A})(0.10\ \text{m})(4.5\ \text{A})I_2}{2\pi(0.005\ \text{m})}$$

$$I_2 = 3.0\ \text{A}$$

Using Ohm's law, the resistance can be calculated.

$$R = \frac{V}{I} = \frac{9.0\ \text{V}}{3.0\ \text{A}} = 3.0\ \Omega$$

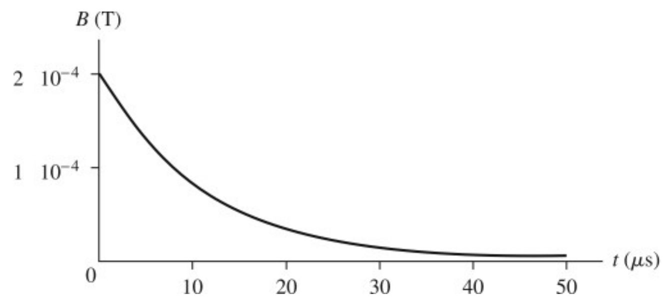
P24.46. Prepare: The resistor and capacitor form an *RC* circuit. Assume that the length of the wire next to the dot is much larger than 1.0 cm.
Solve: As the capacitor discharges through the resistor, the current through the circuit will decrease as

$$I = \frac{V}{R}\exp(-t/(RC)) \text{ or } e^{-t/(RC)} = \frac{50\ \text{V}}{5\,\Omega}\exp(-t((5\ \Omega)(2\ \mu\text{F}))) \text{ or } e^{-t/((5\,\Omega)(2\,\mu\text{F}))} = (10\ \text{A})\exp(-t(10\ \mu\text{s})) \text{ or } e^{-t/(10\,\mu\text{s})}$$

$$\Rightarrow B = \frac{\mu_0 I}{2\pi r} = \frac{\mu_0}{2\pi r}(10\,\text{A})\exp(-t(10\,\mu\text{s})) \text{ or } e^{-t/(10\,\mu\text{s})} = \frac{(2.0\times10^{-7}\ \text{T}\cdot\text{m/A})(10\,\text{A})}{0.010\ \text{m}}\exp(-t(10\ \mu\text{s}))$$

$$\text{or } e^{-t/(10\mu\text{s})} = (2.0\times10^{-4}\ \text{T})\exp(-t(10\ \mu\text{s})) \text{ or } e^{-t/(10\mu\text{s})}$$

The time constant for the exponential decay is $\tau = RC = (5\,\Omega)(2\ \mu\text{F}) = 10\ \mu\text{s}$.
Thus the magnetic field should be maximum at 2.0×10^{-4} T and exponentially decay to zero in a time frame from 0 to $50\ \mu$s (or 5 times the time constant): See the figure.



P24.47. Prepare: An electric and magnetic field exerts two independent forces on the moving electron. The magnitude of the electric force is $\vec{F}_\text{E} = q\vec{E}$ and the direction is the direction of the electric field. The magnitude of the magnetic force is $F_\text{B} = qvB$ and the direction is given by the right-hand rule for forces.
Solve: The electric field is

$$E = \frac{V}{d} = \left(\frac{200\ \text{V}}{0.01\,\text{m}}, \text{down}\right) = (20{,}000\ \text{V/m, down})$$

The force this field exerts on the electron is $\vec{F}_\text{E} = q\vec{E} = -e\vec{E} = (3.2\times10^{-15}\ \text{N, up})$. The electron will pass through without deflection if the magnetic field also exerts a force on the electron such that $\vec{F}_\text{net} = \vec{F}_\text{E} + \vec{F}_\text{B} = \vec{0}$ N or $\vec{F}_\text{E} = -\vec{F}_\text{B}$: i.e., the electric and magnetic forces cancel each other. So, the magnetic force is $\vec{F}_\text{B} = (3.2\times10^{-15}$ N, down). For a negative charge with $\vec{v}$ to the right to have $\vec{F}_\text{B}$ down requires, from the right-hand rule for forces, that the direction of the magnetic field point into the page. The magnitude of the magnetic force on a moving charge is $F_\text{B} = qvB,$ so the needed field strength is

$$B = \frac{F_\text{B}}{ev} = \frac{3.2\times10^{-15}\ \text{N}}{(1.60\times10^{-19}\ \text{C})(1.0\times10^{7}\ \text{m/s})} = 2.0\times10^{-3}\ \text{T} = 2.0\ \text{mT}$$

Thus, the required magnetic field is $\vec{B} =$ (2.0 mT, into page).

P24.48. **Prepare:** A magnetic field exerts a magnetic force on a length of current carrying wire. We ignore gravitational effects and focus on the magnetic effects. The figure shows a wire in a magnetic field that is directed out of the page. The magnetic force on the wire is therefore to the right and will stretch the springs.
Solve: The direction of the magnetic force is to the right; whereas, the direction of the spring forces is to the left. In static equilibrium, the sum of the forces on the wire is zero:

$$\vec{F}_B + \vec{F}_{\text{spring 1}} + \vec{F}_{\text{spring 2}} = \vec{0}\text{ N} \Rightarrow ILB + (-k\Delta x) + (-k\Delta x) = 0 \Rightarrow I = \frac{2k\Delta x}{LB} = \frac{2(10\text{ N/m})(0.01\text{ m})}{(0.20\text{ m})(0.5\text{ T})} = 2.0\text{ A}$$

P24.49. **Prepare:** The current moves through the wire down the page. From the right-hand rule for forces, the wire experiences a force to the right, away from the battery. The force on the wire is given by $F = BIL.$ We will need some formulas from chapter 2 for motion with constant acceleration.
Solve: **(a)** The current through the circuit is given from Ohm's law:

$$I = \frac{\Delta V}{R} = \frac{1.2\text{ V}}{0.85\text{ m}\Omega} = 1410\text{ A}$$

(b) As mentioned in the Prepare section, the force on the wire is to the right. The magnitude of the force is given by:

$$F = BIL = (0.80\text{ T})(1410\text{ A})(1.5\times10^{-1}\text{ m}) = 169\text{ N}$$

which rounds to 170 N.

(c) We can use one of the equations from chapter 2 to get the final speed of the wire, $v_{\text{f}}^2 = v_{\text{i}}^2 + 2a\Delta x.$ The initial speed is $0\text{ m/s}.$ The acceleration is given from Newton's second law:

$$a = F/m = (169\text{ N})/(5.0\times10^{-3}\text{ kg}) = 3.38\times10^4\text{ m/s}^2$$

The final speed is:

$$v_{\text{f}} = \sqrt{2a\Delta x} = \sqrt{2(3.38\times10^4\text{ m/s}^2)(6.0\times10^{-2}\text{ m})} = 64\text{ m/s}$$

Assess: This converts to about $140\text{ mph},$ which is impressive, considering that the device is powered by a 1.2 V battery. On the other hand, the magnetic field which the wire slides through is not insignificant, being about 16,000 times greater than the earth's field.

P24.50. **Prepare:** Electric and magnetic fields exert forces on a moving charge. The fields are uniform throughout the region.
Solve: **(a)** We will first find the net force on the antiproton, and then find the net acceleration using Newton's second law. The magnitudes of the electric and magnetic forces are

$$F_{\text{E}} = eE = (1.60\times10^{-19}\text{ C})(1000\text{ V/m}) = 1.60\times10^{-16}\text{ N}$$
$$F_{\text{B}} = evB = (1.60\times10^{-19}\text{ C})(500\text{ m/s})(2.5\text{ T}) = 2.0\times10^{-16}\text{ N}$$

The directions of these two forces on the antiproton are opposite. $\vec{F}_{\text{B}}$ points down, whereas $\vec{F}_{\text{E}}$ points up, opposite the direction of the electric field. Hence,

$$\vec{F}_{\text{net}} = \vec{F}_{\text{B}} + \vec{F}_{\text{E}} = 2.0\times10^{-16}\text{ N (down)} - 1.60\times10^{-16}\text{ N (up)}$$
$$= 0.40\times10^{-16}\text{ N (down)}$$
$$\vec{F}_{\text{net}} = m\vec{a}$$
$$\vec{a} = \frac{\vec{F}_{\text{net}}}{m} = \frac{0.40\times10^{-16}\text{ N}}{1.67\times10^{-27}\text{ kg}} = 2.4\times10^{10}\text{ m/s}^2\text{ (down)}$$

(b) If $\vec{v}$ were reversed, both $\vec{F}_E$ and $\vec{F}_B$ will point up. Thus,

$$\vec{F}_{\text{net}} = (1.6\times10^{-16}\text{ N} + 2.0\times10^{-16}\text{ N, up}) \Rightarrow \vec{a} = \left(\frac{3.6\times10^{-16}\text{ N}}{1.67\times10^{-27}\text{ kg}} = 2.2\times10^{11}\text{ m/s}^2\text{, up}\right)$$

P24.51. Prepare: Refer to Figure 24.39 for a diagram of an electromagnetic flow meter. The applied magnetic field produces forces on the ions in flowing blood. This creates a separation of positive from negative ions, which produces an electric field and potential difference.
Solve: (a) The force on a charge moving in a magnetic field is given by Equation 24.5. From Figure 24.39, the angle between the magnetic field and the velocity vectors of the ions is $90°$.

$$F = qvB\sin\alpha = (+1.6\times10^{-19}\,\text{C})(0.15\,\text{m/s})(0.25\,\text{T})\sin 90° = 6.0\times10^{-21}\,\text{N}$$

(b) Assuming all the ions in the blood are singly ionized, the magnitude of the electric field needed to counteract the force created by the magnetic field is given by

$$E = \frac{F}{q} = \frac{6.0\times10^{-21}\,\text{N}}{1.6\times10^{-19}\,\text{C}} = 3.8\times10^{-2}\,\text{N/C} = 3.8\times10^{-2}\,\text{V/m}$$

(c) Assuming the ions are all traveling near the surface of the artery, the potential difference is given by

$$V = dE = (0.003\,\text{m})(3.8\times10^{-2}\,\text{V/m}) = 1.1\times10^{-4}\,\text{V}$$

Assess: Magnetic fields affect the ions in blood, creating a charge separation and voltage differences between blood vessel walls.

P24.52. Prepare: This question asks us to find the magnetic force between the wires and the magnetic force between the wires and the earth, and to say which is larger. To calculate the magnetic force between the wires we use Equation 24.17, but we must leave the equation in terms of *L*, which is not given to us. Next, we calculate the force of the earth on the wires using Equation 24.13, leaving this also in terms of *L*. We will see that the value of the earth's force on wires is larger than that of the wires on each other.
Solve:

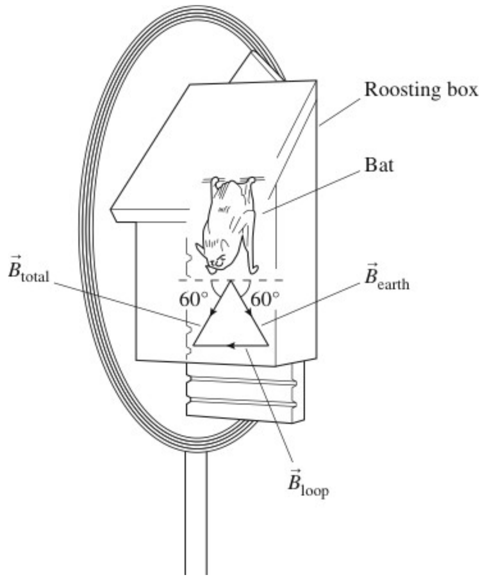
$$F_{\text{wires}} = \frac{\mu_0 L I_1 I_2}{2\pi d} = \frac{(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A})(400\ \text{A})(400\ \text{A})L}{2\pi(5.0\ \text{m})}$$

$$F_{\text{wires}} = (0.0064\ \text{N/m})L$$

$$F_{\text{earth}} = ILB = (400\ \text{A})(5.0\times10^{-5}\ \text{T})L = (0.02\ \text{N/m})L$$

$$F_{\text{earth}} / F_{\text{wires}} \approx 3$$

P24.53. Prepare: As you can see from the figure, the field of the earth, the field of the electromagnet, and the total field form an equilateral triangle. Thus all three sides are the same length. This means that the field of the electromagnet should have a strength of 5.0×10^{-5} T. You can also see from the figure that the field of the electromagnet points south.

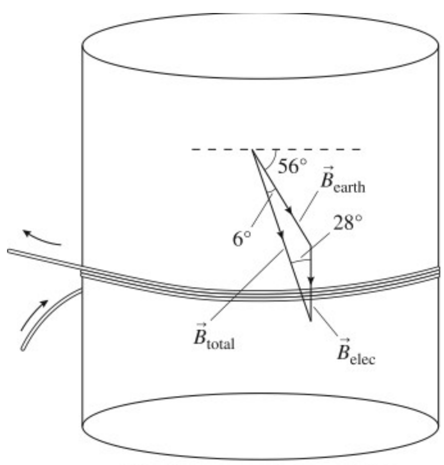


Solve: Since the field of the electromagnet must point south, its axis should be lined up north-south. We find the current by insisting that the total field at the center of the coil be 5.0×10^{-5} T. The field of N loops of wire is given by $B=\dfrac{\mu_0 NI}{2R}$ which we can solve for the current to obtain:

$$I=\frac{2RB}{\mu_0 N}=\frac{(0.50\text{ m})(5.0\times10^{-5}\text{ T})}{(4\pi\times10^{-7}\text{ T}\cdot\text{m/A})(100)}=0.20\text{ A}$$

Assess: The formula $B_{\text{loop}}=\mu_0 I/(2R)$ only applies close to the center of the loop, so for the experiment to be done accurately, the roosting box should be small compared to the size of the loops of wire. Otherwise, a solenoid might be a better choice since it has a nearly uniform magnetic field in its interior.

P24.54. Prepare: Since the coil is horizontally wound, it produced a vertical field at its center. We want to add to the earth's field, $\vec{B}_{\text{earth}}$, which is 56° below the horizontal, to get a total field, $\vec{B}_{\text{total}}$, which is 60° below the horizontal. Thus our electromagnet should have a downward field, $\vec{B}_{\text{elec}}$. From the right-hand rule for fields, we need a clockwise current, as seen from above. The figure shows the three magnetic field vectors.



(Angles exaggerated for clarity)

Solve: The triangle shown in the figure is not a right triangle, so sine and cosine cannot be used directly. A good tool for this problem is the law of sines, according to which the ratio of the length of a side of a triangle to the sine of the opposite angle is the same for all three sides. Applying the law of sines to the two sides on the right, we have:

$$\frac{B_{\text{elec}}}{\sin 6^\circ} = \frac{5.0\times10^{-5}\ \text{T}}{\sin 28^\circ} \Rightarrow B_{\text{elec}} = (\sin 6^\circ)\left(\frac{5.0\times10^{-5}\ \text{T}}{\sin 28^\circ}\right) = 1.11\times10^{-5}\ \text{T}$$

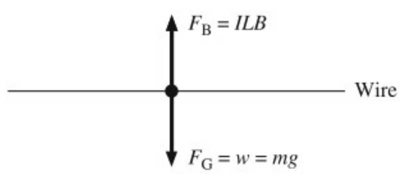
Using the formula for the magnetic field at the center of N loops, $B = \mu_0 NI/(2R)$, we can find the current necessary to achieve this field:

$$I = \frac{2RB}{\mu_0 N} = \frac{(1.2\ \text{m})(1.11\times10^{-5}\ \text{T})}{(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A})(100)} = 0.11\ \text{A}$$

Assess: This seems reasonable since we can compare it to the preceding problem in which the desired field was about four times bigger and the diameter of the coil was about half what it is here. The product of four and one half is two and the current in the previous problem was about twice what it is here.

P24.55. **Prepare:** Imagine a piece of metal in the set which has been magnetized. We don’t know which way its field points so we impose a new field on the piece by exposing the metal to a strong magnetic field in a known direction. But we still have a magnetized piece of metal. We have to get rid of this new field. So we rapidly reverse the direction of the applied field but we don’t let it become as intense in the opposite direction as it was in the original direction. For example, the field might be $1.0\ \text{T}$ in one direction and then we might rapidly change it to $0.90\ \text{T}$ in the opposite direction. The magnetic moments flip back and forth in response to the external field but the induced field is steadily decreasing since we decrease the applied field each time we change its direction. Eventually, the piece of metal will have an immeasurably small field and will no longer distort the picture on the screen.
Assess: Since you cannot make a piece of metal have zero magnetic dipole by exposing it to zero applied field (which would be, essentially, doing nothing), we have to use this bizarre direction reversing approach in which the applied field is gradually reduced to zero. Some television and computer monitors undergo this process, known as degaussing, every time they are turned on. This is why you may see the image shake back and forth for a short time after turning the device on.

P24.56. **Prepare:** The wire will float in the magnetic field if the magnetic force on the wire points upward and balances the gravitational force (mg) on the wire that points downward:



Solve: The net force acting on the wire is $F_{\text{net}} = F_B - F_g = 0$ or $F_B = F_g$. Solving for the magnitude of the magnetic field yields:

$$ILB = mg$$

$$B = \frac{mg}{IL}$$

The problem does not give the mass of the wire, but says the wire is copper and has a length of 1.0 m and a diameter of 0.1 cm. Looking up the mass density of copper, the mass of the wire can be written as

$$\rho = \frac{\text{mass}}{\text{volume}} = \frac{m}{\pi r^2 L}$$

$$m = \rho\pi r^2 L$$

Thus the magnetic field becomes

$$B = \frac{\rho\pi r^2 Lg}{IL} = \frac{\rho\pi r^2 g}{I} = \frac{(8920\ \text{kg/m}^3)\pi(5.0\times10^{-4}\ \text{m})^2(9.8\ \text{m/s}^2)}{(50.0\ \text{A})} = 1.4\times10^{-3}\ \text{T}$$

Direction of $\vec{B}$ is north.

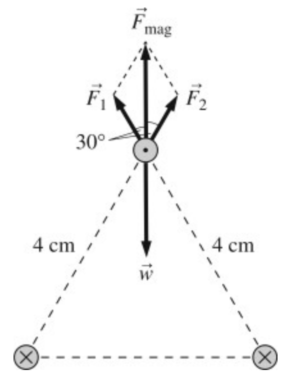
P24.57. Prepare: We must start with the normal equation for a coil, Equation 24.4. Once we've calculated the magnetic field, it is simply a matter of multiplying it by a factor of 100.
Solve:

$$B_{\text{coil}} = \mu_0\left(\frac{N}{L}\right)I = \frac{(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A})(240)(0.60\ \text{A})}{0.018\ \text{m}}$$

$$B_{\text{coil}} = 0.01\ \text{T}$$

$$B_{\text{in coil}} = 0.01\ \text{T}\ (100) = 1.0\ \text{T}$$

P24.58. Prepare: The wire will float in the magnetic field if the magnetic force on the wire points upward and balances the gravitational force (mg) on the wire that points downward. See the figure.



Solve: Each lower wire exerts a repulsive force on the upper wire because the currents are equal in magnitude and opposite in directions: $F_{B-1} = F_{B-2}$. Consider segments of the wires of length L. Then the forces are

$$F_1 = F_2 = \frac{\mu_0 LI^2}{2\pi d}$$

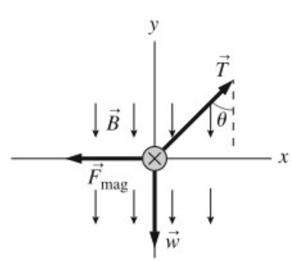
The horizontal components of these two forces cancel, so the net magnetic force is upward and of magnitude

$$F_{\text{mag}} = F_1\cos30° + F_2\cos30° = 2F\cos30° = \frac{2\mu_0 LI^2\cos30°}{2\pi d}$$

In equilibrium, this force must exactly balance the downward weight of the wire (mg). The wire's linear mass density is μ = 0.050 kg/m, so the mass of this segment is $m = \mu L$ and its weight is $w = mg = \mu Lg$. Equating these gives

$$\frac{\mu_0 LI^2\cos(30°)}{\pi d} = \mu Lg \Rightarrow I = \sqrt{\frac{\mu g\pi d}{\mu_0\cos30°}} = \sqrt{\frac{(0.050\ \text{kg/m})(9.8\ \text{m/s}^2)\pi(0.040\ \text{m})}{(4\pi\times10^{-7}\ \text{T}\cdot\text{m/A})\cos30°}} = 240\ \text{A}$$

P24.59. Prepare: A magnetic field exerts a magnetic force on the length of a current-carrying wire.



Solve: The figure shows a side view of the wire, with the current moving into the page. From the right-hand rule, the magnetic field $\vec{B}$ points *down* to give a leftward force on the current. The wire is hanging in static equilibrium, so $\vec{F}_{\text{net}} = \vec{F}_{\text{mag}} + \vec{w} + \vec{T} = 0$ N.

Consider a segment of wire of length L. The wire's linear mass density is $\mu = 0.050$ kg/m, so the mass of this segment is $m = \mu L$ and its weight is $w = mg = \mu Lg$. The magnetic force on this length of wire is $F_{mag} = ILB$. In component form, Newton's first law is

$$(F_{net})_x = T\sin\theta - F_B = T\sin\theta - ILB = 0\text{ N} \Rightarrow T\sin\theta = ILB$$
$$(F_{net})_y = T\cos\theta - w = T\cos\theta - \mu Lg = 0\text{ N} \Rightarrow T\cos\theta = \mu Lg$$

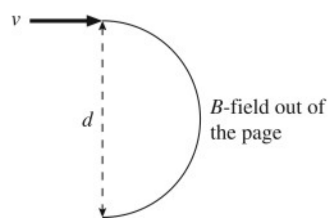
Dividing the first equation by the second,

$$\left[\frac{T\sin\theta}{T\cos\theta} = \tan\theta\right] = \left[\frac{ILB}{\mu Lg} = \frac{IB}{\mu g}\right] \Rightarrow B = \frac{\mu g\tan\theta}{I} = \frac{(0.050\text{ kg/m})(9.8\text{ m/s}^2)\tan 10°}{10\text{ A}} = 0.0086\text{ T}$$

The magnetic field is $\vec{B} = (0.0086\text{ T, down})$.

Assess: This problem tests your knowledge of forces and equilibrium. For the wire to be in equilibrium, all the forces on it must cancel. Also, it is important to note that the wire does not exert a force on itself, so only the external magnetic field exerts a force. The vertical and horizontal components of the tension must equal the weight and the magnetic force respectively, as shown by Newton's first law.

P24.60. Prepare: Picture the setup of a mass spectrometer. A particle enters a magnetic field and is moved in a semicircular path. The radius of the circle is given by $r = mv/qB$, but the net distance traveled by the ion is the diameter of the circle.

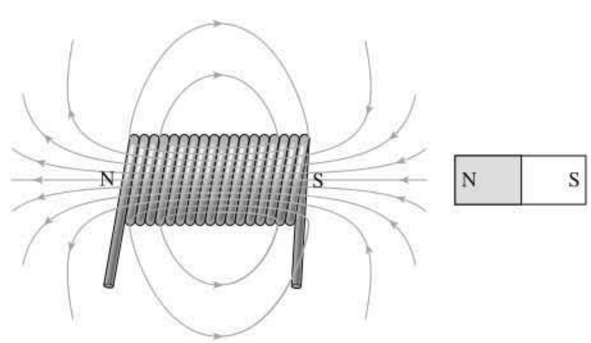


Solve: The isotopes are each singly ionized so the charge on each is $q = 1.60 \times 10^{-19}$ C. For the mass, we use the atomic masses listed in the table given in the problem text. The total distance traveled is therefore:

$$d_{12} = 2r_{12} = \frac{2(1.99\times10^{-26}\text{ kg})(1.5\times10^5\text{ m/s})}{(1.60\times10^{-19}\text{ C})0.200\text{ T}} = 18.7\text{ cm}$$
$$d_{13} = 2r_{13} = \frac{2(2.16\times10^{-26}\text{ kg})(1.5\times10^5\text{ m/s})}{(1.60\times10^{-19}\text{ C})0.200\text{ T}} = 20.2\text{ cm}$$
$$d_{14} = 2r_{14} = \frac{2(2.33\times10^{-26}\text{ kg})(1.5\times10^5\text{ m/s})}{(1.60\times10^{-19}\text{ C})0.200\text{ T}} = 21.8\text{ cm}$$

Assess: The more massive the particle, the further it travels from its entrance into the magnetic field. This is how the mass spectrometer separates particles of different masses.

P24.61. Prepare: By the right-hand rule, the clockwise current in the solenoid will produce a magnetic field pointing to the left. This will induce a dipole moment in the iron.
Solve: (a) See the figure.



(b) The field from the solenoid will create a dipole moment pointing to the left (north pole left, south pole right). This will induce a dipole moment in the same direction in the iron. The force between the two fields will be attractive, pulling the iron to the left toward the solenoid.
(c) To the left toward the solenoid.

P24.62. **Prepare:** The magnetic and electric fields are uniform. The electric field points up and the magnetic field points out of the page.
Solve: The magnetic force on a moving charged particle is perpendicular to both the direction in which the particle is moving and the direction of the magnetic field. We can use the right-hand rule to determine the direction of the magnetic force. Also, note that the particle is positively charged. Using the right-hand rule, we determine that the magnetic force points downward toward the bottom of the paper.
The electric force points upward. The answer is A.

P24.63. **Prepare:** We assume gravity does not affect the particle.
Solve: The kinetic energy is dependent on the velocity. It increases if the velocity increases and decreases if the velocity decreases. For the undeflected particle, the velocity is constant since the force due to the electric field is equal to the force due to the magnetic field. The velocity of the undeflected particle is $v = E/B$.
Since both E and B are constant, the velocity is also constant, and we can conclude that the kinetic energy is constant. The answer is, therefore, B.

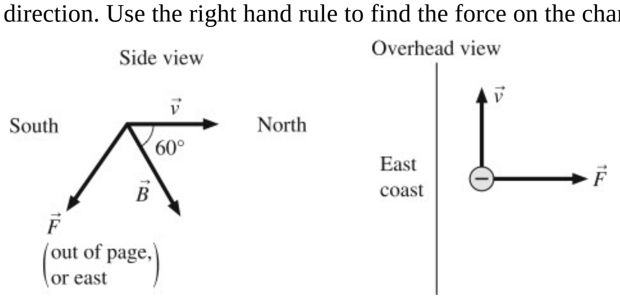
P24.64. **Prepare:** The magnetic force is proportional to the velocity of the particle since $F = |q|vB\sin\alpha$.
Solve: Increasing the velocity of the particle would increase the magnetic force on it. The electric force is independent of the velocity, thus increasing the particle's velocity would not affect the electric force it feels. The resultant force on the particle is a sum of the magnetic and electric forces. For the undeflected particle, the resultant force is 0. Increasing the magnetic force component would cause the particle to deflect in the direction of the magnetic force. The direction of the magnetic force is determined using the right-hand rule. Since the magnetic force points downward, the particle would be deflected downward, toward the bottom of the page. The answer is B.

P24.65. **Prepare:** For the initial undeflected particle, the electric force and the magnetic force cancel out, and q$E = qvB$.
Solve: Now if we double the charge q, the electric force and the magnetic force both increase by a factor of 2.

$$(2q)E = (2q)vB$$
$$E = vB$$
$$v = \frac{E}{B}$$

We see from the final equation for the velocity v, that the particle remains undeflected. The answer is C.

P24.66. **Prepare:** The charge moves northward with the current and the magnetic field points 60° below the horizontal, in the northern direction. Use the right hand rule to find the force on the charge.



Solve: Point the thumb of your right hand in the northern direction (for the velocity) and your index finger 60° below the horizontal, in the northern direction (for the magnetic field). Then your middle finger will point west if you orient your hand as described in the text. However, since this is a negative charge, we have to take the opposite of the direction predicted by the right-hand rule. Thus the force on the ion points east. The correct choice is A.

Assess: Don't forget to reverse the result predicted by the right-hand rule if you are considering a negative charge. Notice that even though the velocity and magnetic field are not perpendicular in this problem, the force is perpendicular to both.

P24.67. Prepare: We can find the force on the ion using the formula $F = |q|vB\sin\alpha$. The angle α is the angle between the velocity and the magnetic field, 60°. Since the charged particle is a singly ionized negative ion, the charge q is the charge of an electron: $q = 1.60\times10^{-19}$ C.
Solve: Plugging the data into the formula for the force, we get:

$$F = (1.60\times10^{-19}\text{ C})(3.5\text{ m/s})(5\times10^{-5}\text{ T})\sin(60^\circ) = 2.4\times10^{-23}\text{ N}$$

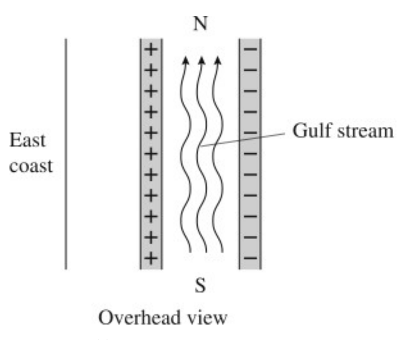
The correct choice is B.
Assess: This is a very tiny force, but a chlorine ion has a mass of only about 5.89×10^{-26} kg, so if this force acts alone, the acceleration of the ion is, from Newton's second law: $a = F/m = (2.4\times10^{-23}\text{ N})/(5.89\times10^{-26}\text{ kg}) = 407\text{ m/s}^2 = 42g$.

P24.68. Prepare: The magnetic force is, as seen in problem 24.67, given by $F_{\text{mag}} = |q|vB\sin\alpha$ and the electric forces is given by $F_{\text{elec}} = |q|E$.
Solve: We set the two forces equal to one another to obtain:

$$|q|E = |q|vB\sin\alpha \Rightarrow$$
$$E = vB\sin\alpha = (3.5\text{ m/s})(5\times10^{-5}\text{ T})\sin60^\circ = 1.5\times10^{-4}\text{ N/C}$$

The correct choice is B.
Assess: The electric field magnitude depends on the angle α because the more nearly perpendicular the velocity and magnetic field are, the stronger the magnetic force which needs to be overcome by the electric field. If, for instance, the velocity and magnetic field were parallel, there would be no magnetic force and so no electric field.

P24.69. Prepare: As seen in problem 24.66, the negative ions are pushed east (and any positive ions are pushed west). If you think of the ocean current as being like a capacitor with two vertical plates oriented north-south, then the negative plate would be on the eastern edge of the current and the positive plate would be on the western edge. Thus the potential decreases from west to east.



Solve: To measure the greatest potential difference, the second electrode should be east or west of the first electrode. In A and B, the second electrode is higher or lower than the first but not positioned to the east or west. In C, the second electrode is north of the first, again neither east nor west. Thus in A, B, and C, the potential difference would be zero. Only in D is there an east-west separation between the electrodes. The correct choice is D.
Assess: In D, the two electrodes are at the same level and the second electrode is directly east of the first. However, continuing the analogy of the capacitor, just as a capacitor's plates are equipotential surfaces, the second electrode could be raised or lowered or moved north or south without changing its separation from the first electrode in the east-west direction and without changing the potential difference between the electrodes.