Question 1: Mathematical Routines (MR) — 10 points

A (i) For indicating that the magnetic field is directed into the page in Figure 2 — **Point A1**

For indicating **one** of the following: — **Point A2**

- The magnetic force is directed in the $+y$ -direction in Figure 3.
- If the direction is out of the page in Figure 2, the magnetic force is directed in the $-y$ -direction in Figure 3.

Example Response

Magnetic Field from Wire 2 at Point P

Figure 2

Magnetic Force on Wire 1 by Wire 2

Figure 3

(ii) For a multistep derivation that includes $B = \dfrac{\mu_0 I}{2\pi r}$, $\sum \vec{F} = 0$, an equation that is equivalent to one of the equations listed, or a relevant equation — **Point A3**

Scoring Note: Vector notation is not required for this point to be earned.

For a correct expression for the magnitude of the magnetic field due to the current in Wire 2 along Wire 1 (e.g., $B_2 = \dfrac{\mu_0 I}{2\pi d}$) — **Point A4**

For a substitution of $2I$ for a current term in **one** of the following expressions: — **Point A5**

- The magnitude of the magnetic field due to the current in Wire 3 along Wire 1 (e.g., $\dfrac{\mu_0 (2I)}{2\pi d_3}$)
- The magnitude of the magnetic force exerted on Wire 1 due to the current in Wire 3 (e.g., $I\ell \dfrac{\mu_0 (2I)}{2\pi d_3}$)

For equating the magnitudes of the magnetic fields from or the force per unit length exerted by the currents in wires 2 and 3 along Wire 1, consistent with point A5 (e.g., $\dfrac{\mu_0 I}{2\pi d} = \dfrac{\mu_0 (2I)}{2\pi d_3}$) — **Point A6**

For a correct expression for $|y_3|$ (e.g., $|y_3| = 2d$) — **Point A7**

Scoring Note: A correct, isolated, final expression earns points A4, A5, A6, and A7.

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Example Response

$$B = \frac{\mu_0 I}{2\pi r}$$

$$B_2 = \frac{\mu_0 I}{2\pi d}$$

$$B_3 = \frac{\mu_0 (2I)}{2\pi d_3}$$

$$B_2 = B_3$$

$$\frac{\mu_0 I}{2\pi d} = \frac{\mu_0 (2I)}{2\pi d_3}$$

$$d_3 = 2d$$

$$y_3 = -2d$$

B For indicating that the induced current in the loop is clockwise — **Point B1**

For indicating **one** of the following: — **Point B2**

- The direction of the magnetic field due to the currents in wires 1 and 2 is into the page inside the loop.
- The magnetic flux through the loop due to the currents in wires 1 and 2 is into the page.

For correctly relating the change in the absolute value of the magnetic flux to the direction of the induced magnetic field produced by the induced current in the loop — **Point B3**

Scoring Note: This point is checking for a correct application of Lenz’s law to the direction of the magnetic field chosen in point B2.

Example Response

Clockwise. The magnetic field from wires 1 and 2 is directed into the page within the loop, and the absolute value of the magnetic flux through the loop decreases as the loop moves away from the wires. This means that the induced magnetic field produced by the induced current in the loop must also be into the page.

Question 4: Short Answer/Other — 10 points

(a) For indicating that the final kinetic energy of a particle is equal to $|q\Delta V|$ — **1 point**

Scoring Note: Explicit indication of an absolute value is not required for this point to be earned.

Example Response

$$|q\Delta V| = K$$

For $\dfrac{K_2}{K_1} = 2$ — **1 point**

Example Solution

$$E_0 = E_f$$
$$\Delta U + \Delta K = 0$$
$$-\Delta U_E = \Delta K$$
$$|q\Delta V| = K$$

$$K_1 = |-Q\Delta V| = Q\Delta V$$

$$K_2 = |+2Q\Delta V| = 2Q\Delta V$$

$$\frac{K_2}{K_1} = \frac{2Q\Delta V}{Q\Delta V}$$
$$\frac{K_2}{K_1} = 2$$

Total for part (a) — **2 point**

Scoring Note: Parts (b)(i) and (b)(ii) can be scored together.

(b)(i) For a correct expression for the speed of Particle 2 in terms of K_2 and M — **1 point**

Example Response

$$v = 2\sqrt{\frac{K_2}{M}}$$

Example Solution

$$K = \frac{1}{2}mv^2$$
$$K_2 = \frac{1}{2}\left(\frac{M}{2}\right)v^2$$
$$v = 2\sqrt{\frac{K_2}{M}}$$

(b)(ii) For substituting an appropriate expression for the magnetic force exerted on a moving charged particle in a magnetic field into a Newton's second law equation — **1 point**

Example Response

$$\vec{a}_c = \frac{q\vec{v} \times \vec{B}}{m}$$

For correct substitutions of the mass, charge, and speed of Particle 2 from the response in part (b)(i) into an appropriate expression — **1 point**

Example Response

$$r = \frac{\left(\frac{M}{2}\right)\left(2\sqrt{\frac{K_2}{M}}\right)}{2QB_0}$$

For indicating that $\Delta x = 2r$ — **1 point**

Example Solution

$$\vec{a} = \frac{\sum \vec{F}}{m}$$
$$\vec{a}_c = \frac{q\vec{v} \times \vec{B}}{m}$$
$$\frac{v^2}{r} = \frac{qvB}{m}$$
$$r = \frac{mv}{qB}$$

$$r = \frac{\left(\frac{M}{2}\right)\left(2\sqrt{\frac{K_2}{M}}\right)}{2QB_0}$$

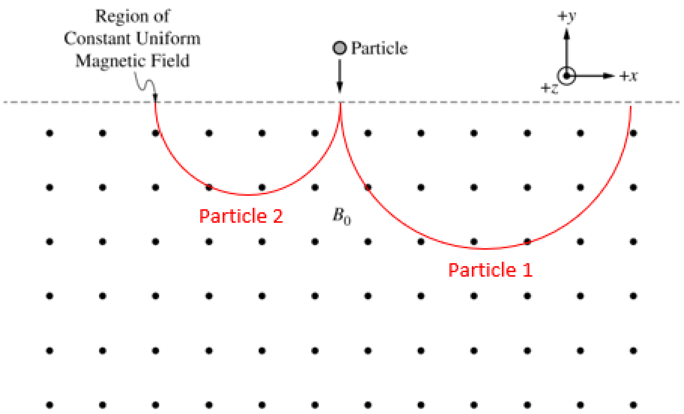
$$r = \frac{\sqrt{K_2 M}}{2QB_0}$$

$$\Delta x = 2r$$
$$\Delta x = \frac{\sqrt{K_2 M}}{QB_0}$$

Total for part (b) — **4 points**

(c)	For drawing a path for Particle 1 that is concave up and to the right	**1 point**
	For drawing a path for Particle 2 that is concave up and in the opposite direction of Particle 1	**1 point**
	For drawing the path for Particle 1 with a larger radius of curvature than the path for Particle 2	**1 point**

Example Response



Total for part (c) **3 points**

(d)	For indicating **one** of the following:	**1 point**

- That the electric field is directed in the $+x$-direction
- A direction of the electric field that is consistent with the path of Particle 1 drawn in part (c)

Example Response

$+x$-direction

Total for part (d) **1 point**

Total for question 4 **10 points**

Question 4: Short Answer — 10 points

(a)	For an appropriate use of Newton's laws to set the magnetic force equal to the electric force	**1 point**
	For using correct expressions for the magnetic and electric forces	**1 point**
	For substituting an expression for the magnetic field to yield a correct expression that includes v and the given quantities	**1 point**

Example Response

$$\Sigma\vec{F} = m\vec{a}$$

$$F_M - F_E = 0$$

$$F_M = F_E$$

$$qvB = qE$$

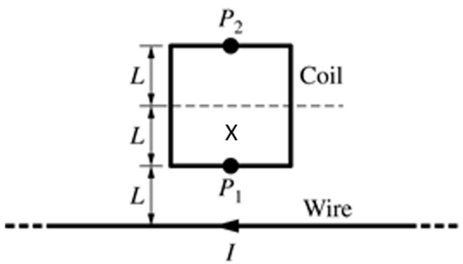
$$v\left(\frac{\mu_0 I}{2\pi d}\right) = E$$

$$v = \frac{2\pi dE}{\mu_0 I}$$

Total for part (a) **3 points**

(b)(i)	For an "X" between point P_1 and the dashed line	**1 point**

Example Response



For indicating that the magnetic field strength is inversely proportional to the distance from the wire — **1 point**

Example Response

Magnetic field is inversely proportional to the distance from a long, straight current carrying wire: $B = \frac{\mu_0 I}{2\pi r}$. Doubling the distance from the wire from L to $2L$ would reduce the magnetic field from $3B_0$ to $1.5B_0$. Therefore, the magnetic field would be equal to $2B_0$ somewhere between L and $2L$.

(b)(ii)	For using the change in flux, with correct substitutions, to determine the emf	**1 point**
	For correctly applying Ohm's law with correct substitutions	**1 point**
	Scoring Note: It is not necessary to independently calculate a numerical value for the emf.	
	Example Response $\lvert\mathcal{E}\rvert = \left\lvert -\frac{\Delta\Phi_B}{\Delta t}\right\rvert = \frac{\left(5.0\times10^{-5} - 1.0\times10^{-5}\right)\ \text{T}\bullet\text{m}^2}{2.0\ \text{s}} = 2.0\times10^{-5}\ \text{V}$ $I = \frac{\lvert\mathcal{E}\rvert}{R} = \frac{2.0\times10^{-5}\ \text{V}}{10\ \Omega} = 2.0\times10^{-6}\ \text{A}$	
	Total for part (b)	**4 points**
(c)	For indicating that the current in the round coil produces a magnetic field	**1 point**
	For indicating that the magnetic field from the round coil produces a flux through the square coil	**1 point**
	For indicating that the changing flux produces an emf or current in the square coil circuit **Scoring Note:** A response that indicates that the magnetic flux only changes during a portion of the entire time interval does not earn this point.	**1 point**
	Example Response *The current in the round coil produces a magnetic field. The magnetic field from the round coil passes through the square coil, producing a flux. As the current in the power supply increases, so does the current in the round coil, and, therefore, the magnetic field created by the current increases. Since the magnetic field changes, the flux through the square coil changes. The constantly changing magnetic flux through the square coil produces an emf and, therefore, current in the square coil to light the lightbulb.*	
	Total for part (c)	**3 points**
	Total for question 4	**10 points**