

---

# AP<sup>®</sup> AP Physics C: Electricity & Magnetism

## Sample Student Responses and Scoring Commentary

### Question #1

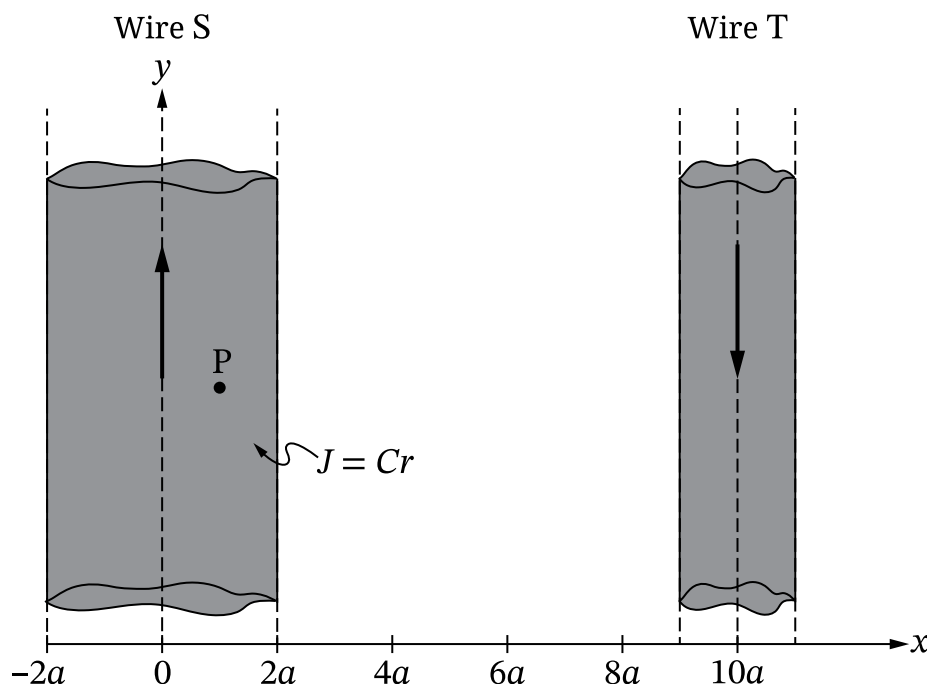
DRAFT

These exam materials may **not** be posted on school or personal websites, nor electronically redistributed for any reason without the express permission of College Board.

These training materials may be used solely for noncommercial purposes by AP teachers and students for course exam preparation. Permission for any other use must be sought from College Board. Teachers may reproduce these training materials in whole or in part, in limited quantities, for noncommercial, face-to-face teaching purposes, as long as the copyright notices are kept intact.

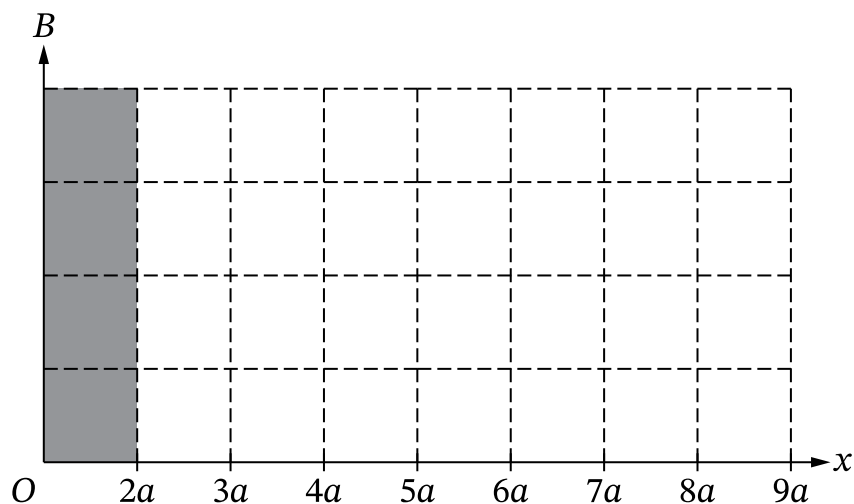
**Question 1: Version J**

1. Two very long, cylindrical, current-carrying Wires S and T are oriented parallel to the  $y$ -axis, as shown in Figure 1. The centers of the wires are in the  $xy$ -plane. The wires are described as follows.
- Wire S has radius  $2a$  and is centered at  $x = 0$ . Wire S has nonuniform current density and carries total current  $I_0$  in the  $+y$ -direction. The magnitude of the current density in Wire S as a function of the radial distance  $r$  from the center of the wire is described by  $J = Cr$ , where  $C$  is a positive constant.
  - Wire T has radius  $a$  and is centered at  $x = 10a$ . Wire T has uniform current density and carries total current  $I_0$  in the  $-y$ -direction.

**Figure 1****Part A**

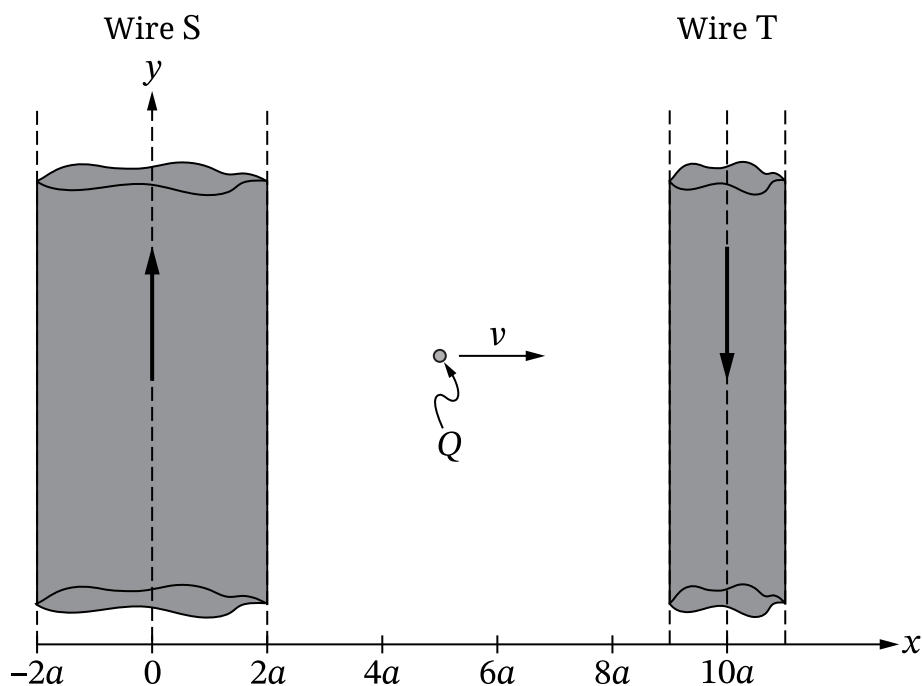
- Point P is located inside of Wire S at horizontal position  $x = a$ . **Derive** an expression for the magnitude of the magnetic field at Point P due only to the current in Wire S in terms of  $C$ ,  $a$ , and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.
- On the axes shown in Figure 2, **sketch** a graph of the magnitude  $B$  of the magnetic field due to the currents in both wires as a function of  $x$  along the  $x$ -axis in the region  $2a \leq x \leq 9a$ . Sketches made in the shaded region will not be graded.

Figure 2

**Part B**

At the instant shown in Figure 3, a small sphere with charge  $Q$  is at horizontal position  $x = 5a$  and moving in the  $xy$ -plane with speed  $v$  in the  $+x$ -direction. At this instant, the net magnetic force exerted on the sphere due to the currents in Wires S and T has magnitude  $F$ .

Figure 3



**Derive** an expression for  $F$  in terms of  $a$ ,  $Q$ ,  $I_0$ ,  $v$ , and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

**Question 1 Mathematical Routines (MR)****10 points****General Scoring Notes****NR (No Response):** A score of NR is only assigned to responses that are blank.

- A (i)** For a multistep derivation that includes the equation  $\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I_{\text{enc}}$  or an equivalent equation **Point A1**

**Scoring Note:** Vector notation and line integral notation are not required for this point to be earned.

For indicating that  $\oint d\ell = 2\pi a$  **Point A2**

**Scoring Note:** Line integral notation is not required for this point to be earned.

For substituting  $dA = 2\pi r dr$  and  $J = Cr$  into  $I = \int \vec{J} \cdot d\vec{A}$  **Point A3**

**Scoring Note:** Limits of integration are not required for this point to be earned.

For limits of integration from 0 to  $a$  for the current integral (e.g.,  $I_{\text{enc}} = \int_0^a J dA$ ) **Point A4**

For a correct expression (e.g.,  $B = \frac{\mu_0}{2\pi a} \left( \frac{2\pi C a^3}{3} \right)$ ,  $B = \frac{\mu_0 C a^2}{3}$ , or algebraic equivalent) **Point A5**

**Example Response**

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I_{\text{enc}}$$

$$B(2\pi a) = \mu_0 I_{\text{enc}}$$

$$B = \frac{\mu_0 I_{\text{enc}}}{2\pi a}$$

$$I = \int \vec{J} \cdot d\vec{A}$$

$$dA = 2\pi r dr$$

$$I_{\text{enc}} = \int_0^a Cr(2\pi r dr) = 2\pi C \int_0^a r^2 dr$$

$$I_{\text{enc}} = 2\pi C \left[ \frac{r^3}{3} \right]_0^a = \frac{2\pi C a^3}{3}$$

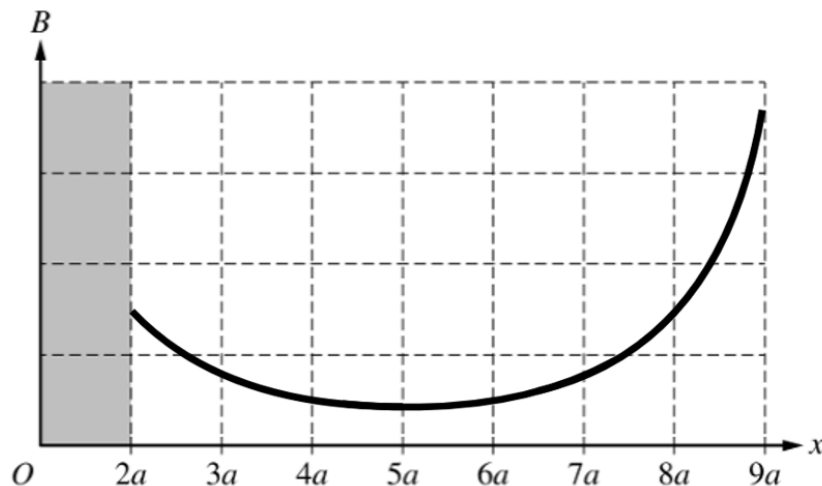
$$\therefore B = \frac{\mu_0}{2\pi a} \left( \frac{2\pi C a^3}{3} \right) = \frac{\mu_0 C a^2}{3}$$

- (ii) For a curve that has a minimum between
- $x = 4a$
- and
- $x = 6a$

Point A6

For a curve that is concave up everywhere with a value at  $x = 9a$  that is greater than the value at  $x = 2a$

Point A7

**Example Response/ Solution**

- B** For a multistep derivation that includes  $\vec{F} = q(\vec{v} \times \vec{B})$

Point B1

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

For indicating that the net magnetic field (or net force) due to the currents in the wires is equal to the combination of the fields (or forces) from both wires

Point B2

For a correct expression (e.g.,  $F = \frac{\mu_0 I_0 Q v}{5\pi a}$ )

Point B3

**Example Response/ Solution**

Wire S

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I_{\text{enc}}$$

$$B_S (2\pi(5a)) = \mu_0 I_0$$

$$B_S = \frac{\mu_0 I_0}{10\pi a}$$

Wire T

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I_{\text{enc}}$$

$$B_T (2\pi(10a - 5a)) = \mu_0 I_0$$

$$B_T = \frac{\mu_0 I_0}{10\pi a}$$

Net Magnetic Field

$$B = B_S + B_T$$

$$B = \frac{\mu_0 I_0}{10\pi a} + \frac{\mu_0 I_0}{10\pi a}$$

$$B = \frac{\mu_0 I_0}{5\pi a}$$

---

$$\vec{F} = q(\vec{v} \times \vec{B})$$

$$F = qvB$$

$$F = \frac{\mu_0 I_0 Q v}{5\pi a}$$

---

Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

### Question 1: Version J

#### PART A

$$A = \pi r^2 \quad dA = 2\pi r dr$$

Figure 2

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I_{\text{enc}}$$

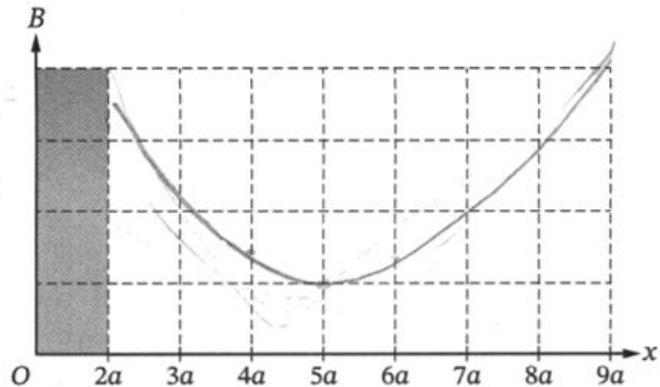
$$I_{\text{enc}} = \int J dA = \int_0^a cr(2\pi r) dr$$

$$\int_0^a 2\pi cr^2 dr = 2\pi c \frac{r^3}{3} \Big|_0^a$$

$$I_{\text{enc}} = \frac{2\pi ca^3}{3}$$

$$B(2\pi a) = \frac{2\pi ca^3}{3} \mu_0$$

$$B = \frac{ca^2 \mu_0}{3}$$



#### PART B

$$F = qvB$$

at  $5a$ :

$$B = \frac{\mu_0 I_0}{2\pi(5a)} + \frac{\mu_0 I_0}{2\pi(5a)} = \frac{\mu_0 I_0}{5\pi a}$$

$$F = \frac{qv\mu_0 I_0}{5\pi a}$$

Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

### Question 1: Version J

#### PART A

$$i) \oint \vec{B} \cdot d\vec{l} = \mu_0 I_{enc}$$

$$B l = \mu_0 I_{enc}$$

$$B(2\pi r) = \mu_0 I_{enc}$$

$$B = \frac{\mu_0 I_{enc}}{2\pi r}$$

$$I_{enc} = \int J dA \quad A = \pi r^2 \quad dA = 2\pi r dr$$

$$I = \int_0^a C r (2\pi r dr)$$

$$= 2\pi C \int_0^a r^2 dr$$

$$= 2\pi C \left[ \frac{r^3}{3} \right]_0^a$$

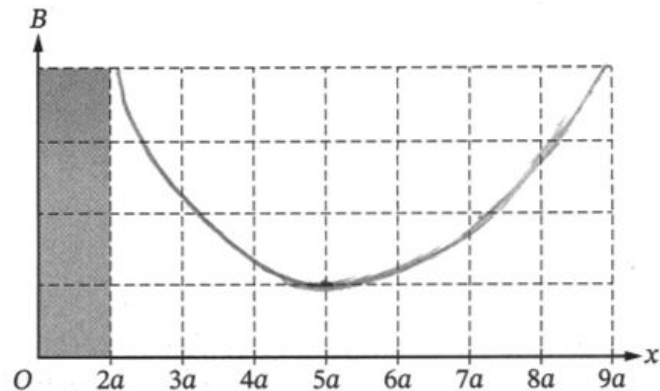
$$= 2\pi C \left[ \frac{a^3}{3} - \frac{0^3}{3} \right]$$

$$= \frac{2\pi C a^3}{3}$$

$$B = \frac{\mu_0 I_{enc}}{2\pi a} = \frac{\mu_0}{2\pi a} \left( \frac{2\pi C a^3}{3} \right)$$

$$= \frac{\mu_0 C a^2}{3}$$

Figure 2



#### PART B

$$F = q\vec{v} \times \vec{B}$$

$$= qvB \sin\theta$$

$$= qvB$$

$$B = B_S + B_T$$

$$= \frac{\mu_0 I_0}{10\pi a} + \frac{\mu_0 I_0}{10\pi a}$$

$$= \frac{\mu_0 I_0}{5\pi a}$$

$$F = qvB$$

$$= qv \left( \frac{\mu_0 I_0}{5\pi a} \right)$$

$$= \frac{\mu_0 I_0 qv}{5\pi a}$$

B from wire S,  $B_S$ :

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{enc}$$

$$B_S l = \mu_0 I_0$$

$$B_S (2\pi(5a)) = \mu_0 I_0$$

$$B_S = \frac{\mu_0 I_0}{10\pi a}$$

B from wire T,  $B_T$ :

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{enc}$$

$$B_T l = \mu_0 I_0$$

$$B_T (2\pi(5a)) = \mu_0 I_0$$

$$B_T = \frac{\mu_0 I_0}{10\pi a}$$

Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

## Question 1: Version J

## PART A

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I_{\text{enc}}$$

$$\frac{I_0}{H(2a)^2} = \frac{I_{\text{enc}}}{\pi(a)^2}$$

$$B(2\pi a) = \mu_0 I_{\text{enc}}$$

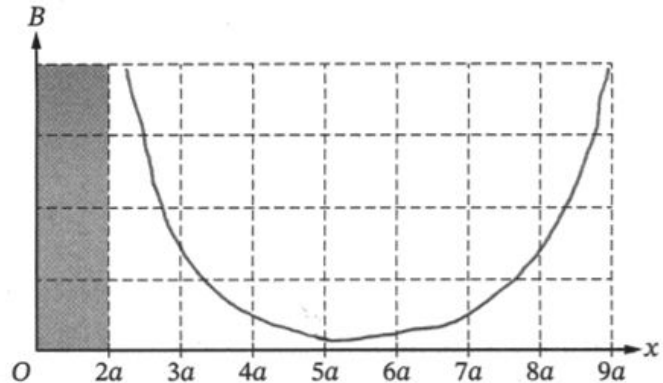
$$B = \frac{\mu_0 I_{\text{enc}}}{2\pi a}$$

$$B_{\text{enc}} = \frac{\mu_0}{2\pi a} \int_0^a j(r) 2\pi r dr$$

$$B = \frac{\mu_0}{2\pi a} \left[ \frac{cr^2}{2} \right]_0^a = \frac{\mu_0 a}{2(2\pi)}$$

$$B = \frac{\mu_0}{2\pi a} \left( \frac{Ca^2}{2} \right) =$$

Figure 2



$$B = \frac{\mu_0 a}{4\pi}$$

## PART B

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I_{\text{enc}}$$

$$B(2\pi r) = \mu_0 I_{\text{enc}}$$

$$B = \frac{\mu_0 I_{\text{enc}}}{2\pi r}$$

$$B_{\text{tot}} = B_S + B_T$$

$$= \frac{\mu_0 I_0}{2\pi(5a)} + \frac{\mu_0 I_0}{2\pi(5a)}$$

$$= \frac{2\mu_0 I_0}{10\pi a}$$

$$\vec{F}_B = q(\vec{v} \times \vec{B})$$

$$= qvB \sin\theta = qvB$$

$$B_{\text{tot}} = \frac{\mu_0 I_0}{5\pi a}$$

$$F_B = q_a v \left( \frac{\mu_0 I_0}{5\pi a} \right)$$

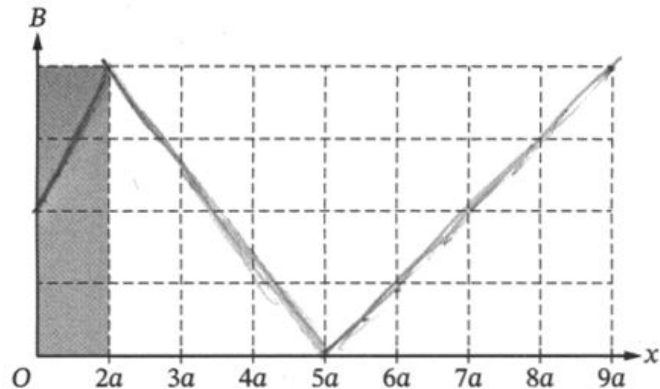
Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

### Question 1: Version J

#### PART A

$$\begin{aligned} 1. \oint \vec{B} \cdot d\vec{\ell} &= \mu_0 I_{enc} \\ B \cdot 2\pi r &= \mu_0 I_{enc} \\ I_{enc} &= \int_0^a C r dr \\ I_{enc} &= C \int_0^a r dr \\ I_{enc} &= \frac{Ca^2}{2} \\ B \cdot 2\pi a &= \mu_0 Ca^2 \\ B &= \frac{\mu_0 Ca}{4\pi} \end{aligned}$$

Figure 2



$$\begin{aligned} B_{sin} &= \frac{\mu_0(r)^2}{4\pi(a)^2} & B_{Tout} &= \frac{\mu_0 I_0}{2\pi(10a-a')} \\ B_{Sout} &= \frac{\mu_0 I}{2\pi(a)} & B_{Tin} &= \frac{\mu_0 I_0}{2\pi(10a+a')} \\ &= \frac{2\mu_0 Ca}{4\pi} & &= \frac{\mu_0 I_0}{16\pi a} \\ &= \frac{\mu_0 I}{6\pi a} & &= \frac{10\mu_0 I_0}{96\pi} = \frac{5\mu_0 I_0}{48\pi} \end{aligned}$$

#### PART B

$$\begin{aligned} \vec{F}_B &= q(\vec{v} \times \vec{B}) & B_A &= B_S - B_T & B_S &= \frac{\mu_0 I_0}{2\pi a'} \\ \vec{F}_B &= qv B_A & B_T &= \frac{\mu_0 I_0}{2\pi(10a-a')} \\ \vec{F}_B &= q\vec{v} \mu_0 I_0 \left( \frac{1}{2\pi a'} - \frac{1}{2\pi(10a-a')} \right) & B_A &= \frac{\mu_0 I_0}{2\pi a'} - \frac{\mu_0 I_0}{2\pi(10a-a')} \end{aligned}$$

Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

## Question 1: Version J

## PART A

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I_{\text{enc}}$$

$$B(2\pi r) = \mu_0 \left( \frac{r^2}{2} \right)$$

$$B_0 = \frac{\mu_0 a}{4\pi}$$

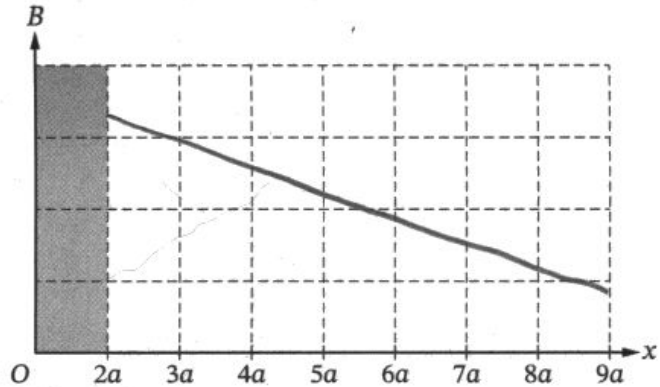
$$ii - \int_0^{2a} B_0 = \int_0^{2a} \left( \frac{\mu_0 r}{2\pi} \right) dr \quad B_{0a} = \frac{\mu_0 2a^2}{2\pi}$$

$$I = 2(a^2) \quad B_{0a} = \frac{\mu_0 2a^2}{2\pi} + \frac{\mu_0 I_0}{2\pi r}$$

$$B+B = \frac{\mu_0 2(a^2)}{2\pi r} + \frac{\mu_0 I_0}{2\pi r}$$

$$I_{\text{enc}} = \left( \frac{r^2}{2} \right)$$

Figure 2



$$B(2\pi r) = \mu_0 I_{\text{enc}}$$

$$B = \frac{\mu_0 I_{\text{enc}}}{2\pi r}$$

$$B_s \downarrow$$
  

$$B_T \uparrow$$

B fields add

## PART B

$$\vec{F}_B = q(\vec{v} \times \vec{B})$$

$$B_{\text{tot}} = \frac{\mu_0 2(a^2)}{2\pi(5a)} + \frac{\mu_0 I_0}{2\pi(5a)} = \frac{\mu_0 (2a^2 + I_0)}{10\pi a}$$

$$F_B = \frac{q v \mu_0 (2a^2 + I_0)}{10\pi a} \quad N \quad \text{up}$$

$$I = 2(a^2)$$

$$I = 2(a^2)$$

Go to Question 2 when you're done with this question.

Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

### Question 1: Version J

#### PART A

Figure 2

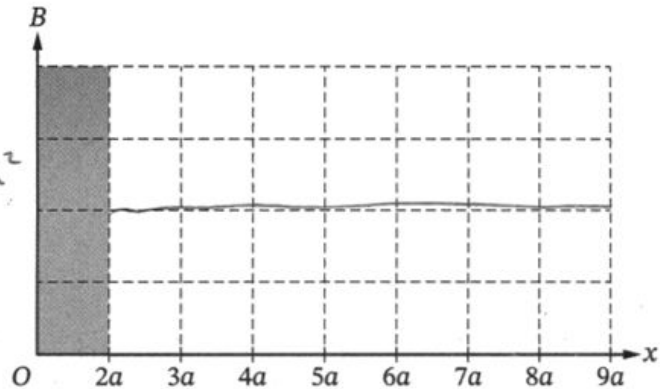
$$i. \oint \vec{B} \cdot d\vec{l} = \mu_0 I_{enc}$$

$$B \cdot a = \frac{\mu_0 C a^2}{2}$$

$$B = \frac{\mu_0 C a}{2}$$

$$I = \int_0^a c_v$$

$$\frac{C}{2} v^2 \Big|_0^a = \frac{C}{2} a^2$$



$$B = \frac{\mu_0 I_0}{4\pi a} + \frac{\mu_0 I_0}{2\pi a}$$

#### PART B

$$\vec{F}_e = q(\vec{v} \times \vec{B})$$

$$\vec{F}_e = Qv \cdot \left( \frac{3\mu_0 I_0}{4\pi a} \right)$$

$$\vec{F}_e = \frac{3Qv\mu_0 I_0}{4\pi a}$$

$$B = \frac{3\mu_0 I_0}{4\pi a}$$

Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

### Question 1: Version J

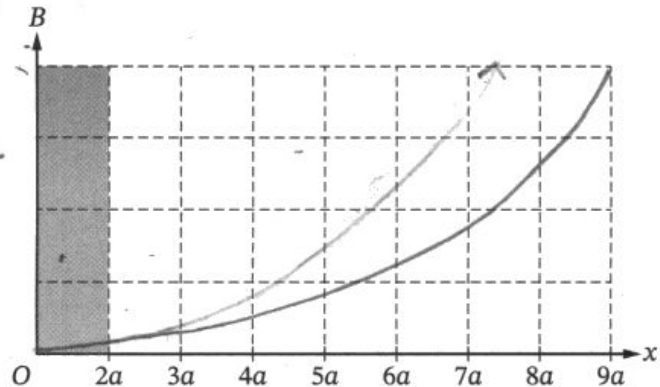
#### PART A

$$\begin{aligned}
 i) B &= \int_{-2a}^a \frac{\mu_0 I \delta l}{4\pi r^2} \\
 B &= \frac{\mu_0 I}{4\pi} \int_{-2a}^a \frac{1}{r^2} dr \\
 B &= \frac{\mu_0 I}{4\pi} \left[ -\frac{1}{r} \right]_{-2a}^a \\
 B &= \frac{\mu_0 I}{4\pi} \left[ -\frac{1}{a} + \frac{1}{-2a} \right] \rightarrow \frac{-2}{2a} = -\frac{1}{a} \\
 B &= -\frac{\mu_0 I}{4\pi a}
 \end{aligned}$$

$dl = dy$   
 $r = 2a$   
 $A = \pi r^2 = 4\pi a^2$   
 $I = \int j \cdot dA$   
 $I = \int c_r$   
 $I = 8\pi a^2 c_a$   
 $= \frac{8\pi a^2 c_a^2}{2}$   
 $I = 4\pi a^2 c_a^2$

$B = \frac{\mu_0 c_a^2}{4\pi} \left[ -\frac{1}{a} + \frac{1}{-2a} \right] \rightarrow \frac{-2}{2a} = -\frac{1}{a}$   
 $B = -\frac{\mu_0 c_a^2}{4\pi a}$

Figure 2



#### PART B

$$F_{net} = F_T + F_S \Rightarrow QvM_0 \left( 125Ia + \frac{I}{10\pi a} \right) = F_{net}$$

$$F_T = qvB = Qv_0(\mu_0 c I 25a)$$

$$B(5) = \mu_0 c I 25a^2$$

$$F_S = qvB = Qv(B) = Qv\left(\frac{\mu_0 I}{10\pi a}\right)$$

$$B(5) = \frac{\mu_0 I}{2\pi 5a} = \frac{\mu_0 I}{10\pi a}$$

Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

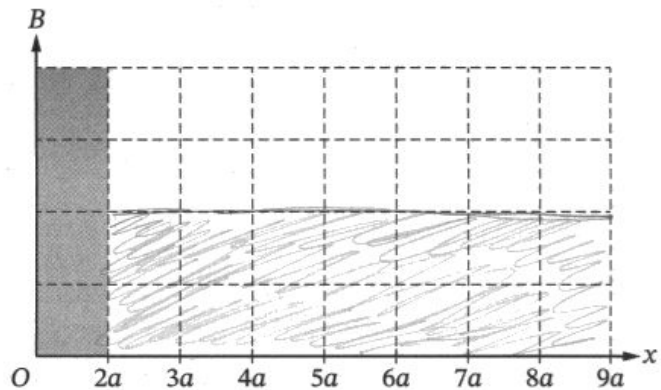
### Question 1: Version J

#### PART A

$$i) \oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 I_{\text{enc}}$$

$$\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 \cdot \int \mathbf{J} \cdot d\mathbf{A}$$

Figure 2



#### PART B

$$F_b = qvB$$

$$F_b = Qv \left( \frac{\mu_0 I_{\text{enc}}}{dl} \right)$$

## Question 1

### Sample Identifier: PCEM Sample 1A

**Score: 10**

- Point A1 was earned. The response includes Ampere’s law and subsequently uses it with an enclosed current evaluation demonstrating a multistep derivation.
- Point A2 was earned. The left side of the Ampere’s law expression is evaluated with a loop length  $2\pi a$ .
- Point A3 was earned. The integral for the enclosed current includes the correct current density,  $Cr$ , and correct differential area element,  $2\pi r dr$ .
- Point A4 was earned. The integral for the enclosed current is evaluated over correct limits from  $r = 0$  to  $r = a$ .
- Point A5 was earned. The correct answer is indicated.
- Point A6 was earned. The drawn curve includes a minimum at  $x = 5a$ .
- Point A7 was earned. The left side of the curve at  $x = 2a$  shows a lower  $B$ -value than the right side at  $x = 9a$ , and the curve is concave up throughout the entire domain  $2a \leq x \leq 9a$ .
- Point B1 was earned. The response includes the necessary force equation and later an expression for the magnetic field is substituted into this expression indicating a multistep derivation.
- Point B2 was earned. The expression for net magnetic field includes one term from each wire.
- Point B3 was earned. The correct final expression is included for the force magnitude.

### Sample Identifier: PCEM Sample 1B

**Score: 9**

- Point A1 was earned. The response includes Ampere’s law and subsequently uses it evaluating the Amperian loop integral demonstrating a multistep derivation.
- Point A2 was earned. The left side of the Ampere’s law expression is evaluated with a loop length  $2\pi r$ , and a later substitution is made for  $r = a$ .
- Point A3 was earned. The integral for the enclosed current includes the correct current density,  $Cr$ , and correct differential area element,  $2\pi r dr$ .
- Point A4 was earned. The integral for the enclosed current is evaluated over correct limits from  $r = 0$  to  $r = a$ .
- Point A5 was earned. The correct answer is indicated.
- Point A6 was earned. The drawn curve includes a minimum at  $x = 5a$ .
- Point A7 was not earned. Even though the curve is concave upward throughout the entire domain  $2a \leq x \leq 9a$ , the left side of the curve at  $x = 2a$  shows the same  $B$ -value as the right side at  $x = 9a$ .
- Point B1 was earned. The response includes the necessary force equation and the specific charge  $Q$  is subsequently substituted into the expression indicating multiple steps.
- Point B2 was earned. The expression for net magnetic field includes a combination from both wires: " $B = B_S + B_T$ ".
- Point B3 was earned. The correct final expression is included for the force magnitude.

**Sample Identifier: PCEM Q1 Sample 1C****Score: 7**

- Point A1 was earned. The response includes Ampere’s law and subsequently uses it with an evaluated Amperian loop integral demonstrating a multistep derivation.
- Point A2 was earned. The left side of the Ampere’s law expression is evaluated with a loop length  $2\pi a$ .
- Point A3 was not earned. The integral for the enclosed current includes the correct current density,  $Cr$ , but an incorrect differential area element,  $dr$ .
- Point A4 was earned. The integral for the enclosed current is evaluated over correct limits from  $r = 0$  to  $r = a$ .
- Point A5 was not earned. An incorrect answer is indicated.
- Point A6 was earned. The drawn curve includes a minimum just to the right of  $x = 5a$ .
- Point A7 was not earned. While the curve is concave upward throughout the entire domain  $2a \leq x \leq 9a$ , the left side of the curve at  $x = 2a$  shows the same  $B$ -value as the right side at  $x = 9a$ .
- Point B1 was earned. The response includes the necessary force equation and it is immediately used indicating a multistep derivation.
- Point B2 was earned. The expression for net magnetic field includes one term from each wire.
- Point B3 was earned. The correct final expression is included for the magnitude of the magnetic force.

**Sample Identifier: PCEM Sample 1D****Score: 6**

- Point A1 was earned. The response includes Ampere’s law and immediately uses it with an evaluated Amperian loop integral demonstrating a multistep derivation.
- Point A2 was earned. The left side of the Ampere’s law expression is evaluated with a loop length  $2\pi a$ .
- Point A3 was not earned. The integral for the enclosed current includes the correct current density,  $Cr$ , but an incorrect differential area element,  $dr$ .
- Point A4 was earned. The integral for the enclosed current is evaluated over correct limits from  $r = 0$  to  $r = a$ .
- Point A5 was not earned. An incorrect answer is indicated.
- Point A6 was earned. The drawn straight lines include a minimum at  $x = 5a$ .
- Point A7 was not earned. The drawn representation is composed of two straight lines throughout domain instead of a concave up curve. Additionally, the left side of the curve at  $x = 2a$  shows the same  $B$ -value as the right side at  $x = 9a$  instead of a lower value at  $x = 2a$ .
- Point B1 was earned. The response includes the necessary force equation, and a net magnetic field is subsequently substituted into it indicating a multistep derivation.
- Point B2 was earned. The expression for net magnetic field includes a combination from both wires.
- Point B3 was not earned. The final force expression is incorrect.

**Sample Identifier: PCEM Sample 1E****Score: 5**

- Point A1 was earned. The response includes Ampere’s law and immediately uses it with an evaluated Amperian loop integral demonstrating a multistep derivation.
- Point A2 was earned. The left side of the Ampere’s law expression is evaluated with a loop length  $2\pi a$ .
- Point A3 was not earned. The integral for the enclosed current includes the correct current density,  $Cr$ , but an incorrect substitution for the differential area element,  $dA = dr$ .
- Point A4 was earned. The correct limits from  $r = 0$  to  $r = a$  are present at the top of the response in the A (i) section, where only the enclosed current is evaluated. The limits seen below the graph are for part A (ii).
- Point A5 was not earned. An incorrect answer is indicated.
- Point A6 was not earned. The drawn curve includes a minimum at  $x = 9a$ .
- Point A7 was not earned. The curve is straight throughout domain  $2a \leq x \leq 9a$ , and the left side of the curve at  $x = 2a$  shows a higher  $B$ -value than the right side at  $x = 9a$ .
- Point B1 was earned. The response includes the necessary force equation, and it is subsequently used indicating a multistep derivation.
- Point B2 was earned. The expression for net magnetic field includes one term from each wire.
- Point B3 was not earned. The final force expression is incorrect.

**Sample Identifier: PCEM Sample 1F****Score: 4**

- Point A1 was earned. The response includes Ampere’s law and immediately uses it with an evaluated Amperian loop integral demonstrating a multistep derivation.
- Point A2 was not earned. The left side of the Ampere’s law expression is evaluated with a loop length of  $a$ .
- Point A3 was not earned. The integral for the enclosed current includes the correct current density,  $Cr$ , but no differential area element is present.
- Point A4 was earned. The integral for the enclosed current is evaluated over correct limits from  $r = 0$  to  $r = a$ .
- Point A5 was not earned. An incorrect answer is indicated.
- Point A6 was not earned. The drawn horizontal line has no minimum.
- Point A7 was not earned. The drawn horizontal line shows a constant value with no concavity.
- Point B1 was earned. The response includes the necessary force equation, and a net magnetic field is substituted into it indicating a multistep derivation.
- Point B2 was earned. The expression for net magnetic field includes a combination from both wires, as seen at the bottom of part A.
- Point B3 was not earned. The final force expression is incorrect.

**Sample Identifier: PCEM Sample 1G****Score: 3**

- Point A1 was not earned. The response includes an equation which is not equivalent to Ampere's law.
- Point A2 was not earned. The only indication of something like an Amperian loop is the expression  $4\pi r^2$  which is not  $2\pi a$ .
- Point A3 was not earned. The integral for the enclosed current includes the correct current density,  $Cr$ , but no differential area element is substituted for the  $dA$ .
- Point A4 was not earned. The integral for the enclosed current has no limits.
- Point A5 was not earned. An incorrect answer is indicated.
- Point A6 was not earned. The drawn curve has a minimum at  $x = 2a$  which is outside the range  $4a < x < 6a$ .
- Point A7 was earned. The drawn curve is concave up throughout the domain and shows a value at  $x = 2a$  below the value at  $x = 9a$ .
- Point B1 was earned. The response includes the necessary force equation, and a net magnetic field is substituted into it indicating a multistep derivation.
- Point B2 was earned. An expression for net force shows a combination field from both wires S and T.
- Point B3 was not earned. The final force expression is incorrect.

**Sample Identifier: PCEM Sample 1H****Score: 2**

- Point A1 was earned. The response includes Ampere's law and immediately uses it with an enclosed current integral.
- Point A2 was not earned. The left side of the Ampere's law expression is not evaluated.
- Point A3 was not earned. The integral for the enclosed current includes no substitutions for either the current density or differential area element terms.
- Point A4 was not earned. The integral for the enclosed current has no limits specified.
- Point A5 was not earned. No answer is indicated.
- Point A6 was not earned. The drawn horizontal line has no minimum.
- Point A7 was not earned. The drawn horizontal line shows a constant value with no concavity.
- Point B1 was earned. The response includes the necessary force equation, and a net magnetic field is substituted into it indicating a multistep derivation.
- Point B2 was not earned. The expression for net magnetic field gives no indication of magnetic fields or forces from two wires.
- Point B3 was not earned. The final force expression is incorrect.