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## 14. Sources of magnetic field: electric currents. Law of Biot and Savart

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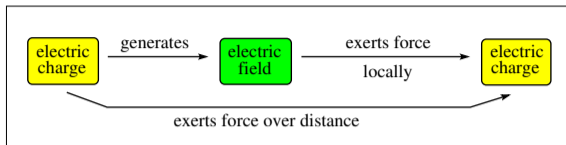
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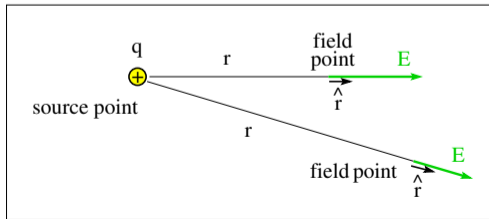


(1) Electric field  $\vec{E}$  generated by point charge  $q$ :  $\vec{E} = k \frac{q}{r^2} \hat{r}$

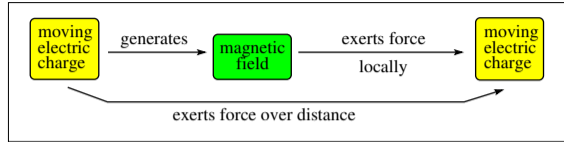
(2) Force  $\vec{F}_1$  exerted by field  $\vec{E}$  on point charge  $q_1$ :  $\vec{F}_1 = q_1 \vec{E}$

(1+2) Force  $\vec{F}_1$  exerted by charge  $q$  on charge  $q_1$ :  $\vec{F}_1 = k \frac{qq_1}{r^2} \hat{r}$  (static conditions)

- $\epsilon_0 = 8.854 \times 10^{-12} \text{C}^2 \text{N}^{-1} \text{m}^{-2}$
- $k = \frac{1}{4\pi\epsilon_0} = 8.99 \times 10^9 \text{Nm}^2 \text{C}^{-2}$
- SI unit of  $E$ : [N/C]



# Magnetic Field of a Moving Point Charge

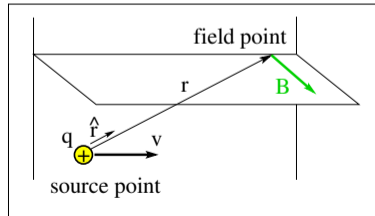


(1) Magnetic field  $\vec{B}$  generated by point charge  $q$ : 
$$\vec{B} = \frac{\mu_0}{4\pi} \frac{q\vec{v} \times \hat{r}}{r^2}$$

(2) Force  $\vec{F}_1$  exerted by field  $\vec{B}$  on point charge  $q_1$ : 
$$\vec{F}_1 = q_1\vec{v}_1 \times \vec{B}$$

(1+2) There is a time delay between causally related events over distance.

- Permeability constant  
 $\mu_0 = 4\pi \times 10^{-7} \text{Tm/A}$



# Magnetic Field Application (1)

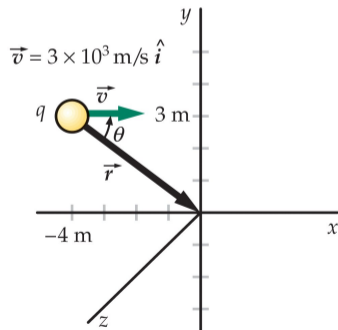


A particle with charge  $q = 4.5\text{nC}$  is moving with velocity  $\vec{v} = 3 \times 10^3\text{m/s}\hat{i}$ .

Find the magnetic field generated at the origin of the coordinate system.

- Position of field point relative to particle:  $\vec{r} = 4\text{m}\hat{i} - 3\text{m}\hat{j}$
- Distance between Particle and field point:  $r = \sqrt{(4\text{m})^2 + (3\text{m})^2} = 5\text{m}$
- Magnetic field:

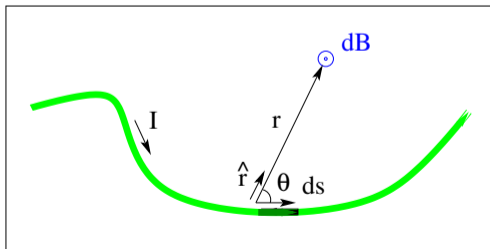
$$\begin{aligned}\vec{B} &= \frac{\mu_0}{4\pi} \frac{q\vec{v} \times \hat{r}}{r^2} = \frac{\mu_0}{4\pi} \frac{q\vec{v} \times \vec{r}}{r^3} \\ &= \frac{\mu_0}{4\pi} \frac{q(3 \times 10^3\text{m/s}\hat{i}) \times (4\text{m}\hat{i} - 3\text{m}\hat{j})}{(5\text{m})^3} \\ &= -\frac{\mu_0}{4\pi} \frac{q(3 \times 10^3\text{m/s}\hat{i}) \times (3\text{m}\hat{j})}{(5\text{m})^3} \\ &= -3.24 \times 10^{-14}\text{T}\hat{k}.\end{aligned}$$





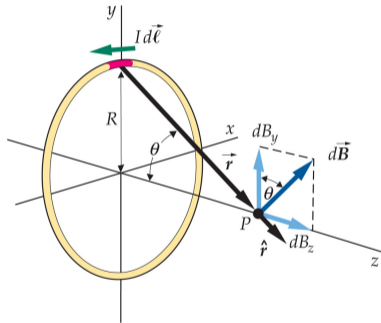
- Current element:  $I d\vec{s} = dq\vec{v}$  [1Am = 1Cm/s]
- Magnetic field of current element:  $dB = \frac{\mu_0}{4\pi} \frac{dqv \sin \theta}{r^2} = \frac{\mu_0}{4\pi} \frac{Ids \sin \theta}{r^2}$
- Vector relation:  $d\vec{B} = \frac{\mu_0}{4\pi} \frac{Id\vec{s} \times \hat{r}}{r^2}$
- Magnetic field generated by current of arbitrary shape:

$$\vec{B} = \frac{\mu_0}{4\pi} \int \frac{Id\vec{s} \times \hat{r}}{r^2} \quad (\text{Law of Biot and Savart})$$





- Law of Biot and Savart:  $dB = \frac{\mu_0}{4\pi} \frac{Id\ell}{z^2 + R^2}$
- $dB_z = dB \sin \theta = dB \frac{R}{\sqrt{z^2 + R^2}}$   
 $\Rightarrow dB_z = \frac{\mu_0 I}{4\pi} \frac{R d\ell}{(z^2 + R^2)^{3/2}}$
- $B_z = \frac{\mu_0 I}{4\pi} \frac{R}{(z^2 + R^2)^{3/2}} \int_0^{2\pi R} d\ell$   
 $\Rightarrow B_z = \frac{\mu_0 I}{2} \frac{R^2}{(z^2 + R^2)^{3/2}}$
- Field at center of ring ( $z = 0$ ):  $B_z = \frac{\mu_0 I}{2R}$
- Magnetic moment:  $\mu = I\pi R^2$
- Field at large distance ( $z \gg R$ ):  $B_z \simeq \frac{\mu_0}{2\pi} \frac{\mu}{z^3}$

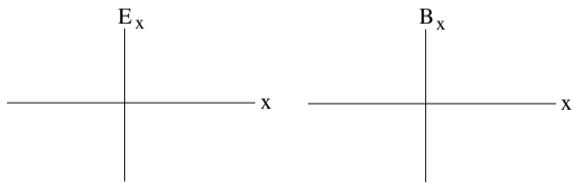




The electric field  $E_x$  along the axis of a charged ring and the magnetic field  $B_x$  along the axis of a circular current loop are

$$E_x = \frac{Q}{4\pi\epsilon_0} \frac{x}{(x^2 + R^2)^{3/2}}, \quad B_x = \frac{\mu_0 I}{2} \frac{R^2}{(x^2 + R^2)^{3/2}}$$

- (a) Simplify both expressions for  $x = 0$ .
- (b) Simplify both expressions for  $x \gg R$ .
- (c) Sketch graphs of  $E_x(x)$  and  $B_x(x)$ .

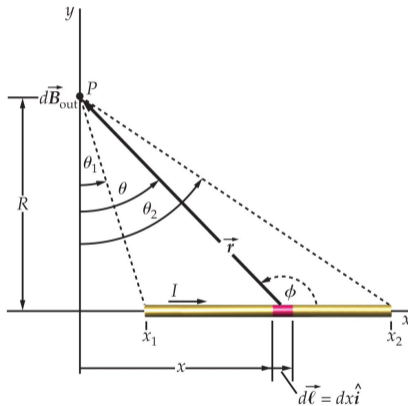


# Magnetic Field Generated by Current in Straight Wire (1)



Consider a field point  $P$  that is a distance  $R$  from the ax

- $dB = \frac{\mu_0}{4\pi} \frac{Idx}{r^2} \sin \phi = \frac{\mu_0}{4\pi} \frac{Idx}{r^2} \cos \theta$
- $x = R \tan \theta \Rightarrow \frac{dx}{d\theta} = \frac{R}{\cos^2 \theta} = \frac{R^2}{R^2/r^2} = \frac{r^2}{R}$
- $dB = \frac{\mu_0}{4\pi} \frac{I}{r^2} \frac{r^2 d\theta}{R} \cos \theta = \frac{\mu_0}{4\pi} \frac{I}{R} \cos \theta d\theta$
- $B = \frac{\mu_0}{4\pi} \frac{I}{R} \int_{\theta_1}^{\theta_2} \cos \theta d\theta$   
 $= \frac{\mu_0}{4\pi} \frac{I}{R} (\sin \theta_2 - \sin \theta_1)$
- Length of wire:  $L = R(\tan \theta_2 - \tan \theta_1)$



Wire of infinite length:  $\theta_1 = -90^\circ$ ,  $\theta_2 = 90^\circ \Rightarrow B = \frac{\mu_0 I}{2\pi R}$

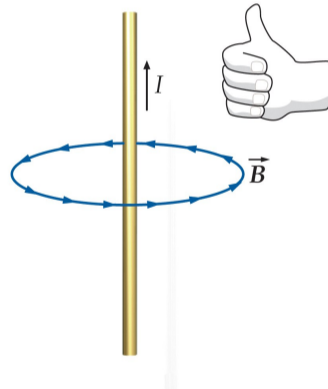


## Magnetic Field Generated by Current in Straight Wire (2)



Consider a current  $I$  in a straight wire of infinite length.

- The magnetic field lines are concentric circles in planes perpendicular to the wire.
- The magnitude of the magnetic field at distance  $R$  from the center of the wire is  $B = \frac{\mu_0 I}{2\pi R}$ .
- The magnetic field strength is proportional to the current  $I$  and inversely proportional to the distance  $R$  from the center of the wire.
- The magnetic field vector is tangential to the circular field lines and directed according to the right-hand rule.

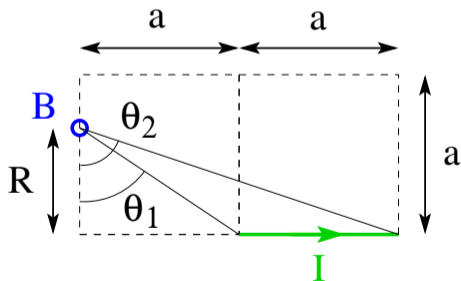


## Magnetic Field Generated by Current in Straight Wire (3)



Consider the magnetic field  $\vec{B}$  in the limit  $R \rightarrow 0$ .

- $B = \frac{\mu_0}{4\pi} \frac{I}{R} (\sin \theta_2 - \sin \theta_1)$
- $\sin \theta_1 = \frac{a}{\sqrt{a^2 + R^2}} = \frac{1}{\sqrt{1 + \frac{R^2}{a^2}}} \simeq 1 - \frac{1}{2} \frac{R^2}{a^2}$
- $\sin \theta_2 = \frac{2a}{\sqrt{4a^2 + R^2}} = \frac{1}{\sqrt{1 + \frac{R^2}{4a^2}}} \simeq 1 - \frac{1}{2} \frac{R^2}{4a^2}$
- $B \simeq \frac{\mu_0}{4\pi} \frac{I}{R} \left( 1 - \frac{1}{2} \frac{R^2}{4a^2} - 1 + \frac{1}{2} \frac{R^2}{a^2} \right)$   
 $= \frac{\mu_0 I}{4\pi} \frac{3R}{8a^2} \xrightarrow{R \rightarrow 0} 0$

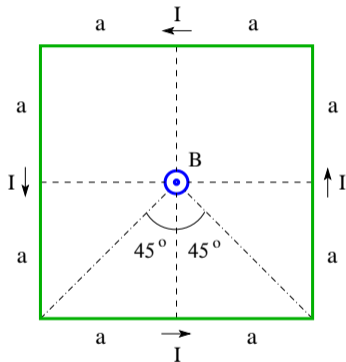




## Magnetic Field at Center of Square-Shaped Wire

Consider a current-carrying wire bent into the shape of a square with side  $2a$ .

Find direction and magnitude of the magnetic field generated at the center of the square.



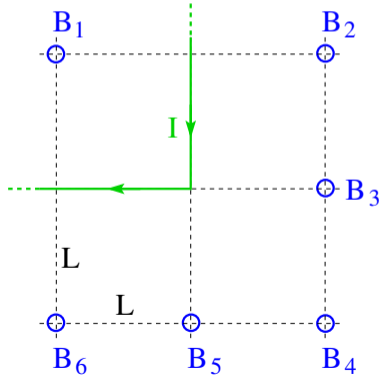
$$B = 4 \frac{\mu_0}{4\pi} \frac{I}{a} \left[ \sin(45^\circ) - \sin(-45^\circ) \right] = \frac{\sqrt{2}\mu_0 I}{\pi a}.$$

## Magnetic Field Application (6)



A current-carrying wire is bent into two semi-infinite straight segments at right angles.

- Find the direction ( $\odot$ ,  $\otimes$ ) of the magnetic fields  $B_1, \dots, B_6$ .
- Name the strongest and the weakest fields among them.
- Name all pairs of fields that have equal strength.

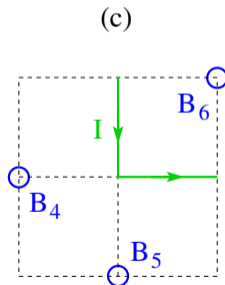
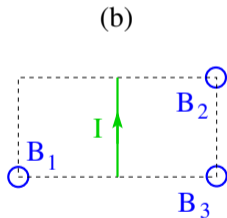
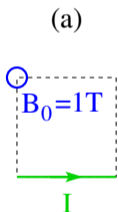


# Magnetic Field Application (5)



If the current  $I$  in (a) generates a magnetic field  $B_0 = 1T$  pointing out of the plane

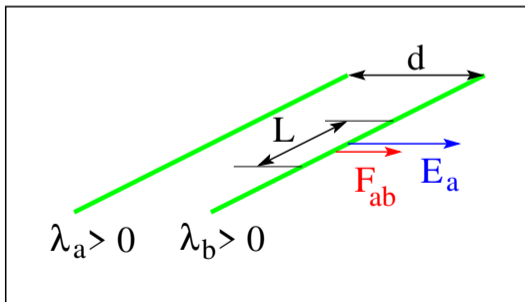
- find magnitude and direction of the fields  $B_1, B_2, B_3$  generated by  $I$  in (b),
- find magnitude and direction of the fields  $B_4, B_5, B_6$  generated by  $I$  in (c).



# Force Between Parallel Lines of Electric Charge



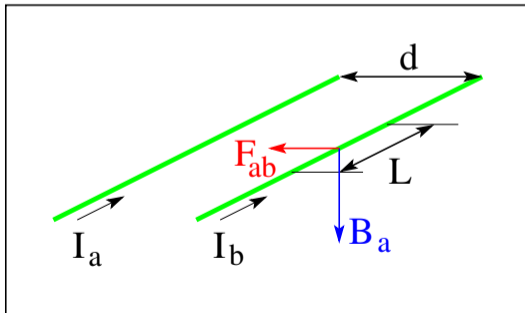
- Electric charge densities:  $\lambda_a, \lambda_b$
- Electric field generated by line  $a$ :  $E_a = \frac{1}{2\pi\epsilon_0} \frac{\lambda_a}{d}$
- Electric force on segment of line  $b$ :  $F_{ab} = \lambda_b L E_a$
- Electric force per unit length (repulsive):  $\frac{F_{ab}}{L} = \frac{1}{2\pi\epsilon_0} \frac{\lambda_a \lambda_b}{d}$



# Force Between Parallel Lines of Electric Current



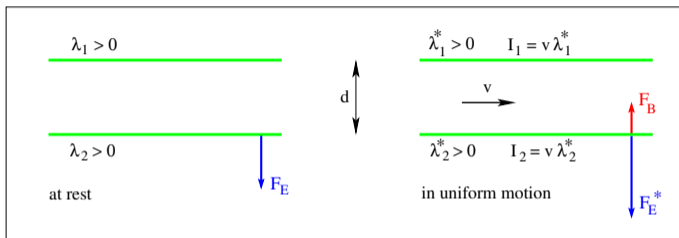
- Electric currents:  $I_a, I_b$
- Magnetic field generated by line  $a$ :  $B_a = \frac{\mu_0 I_a}{2\pi d}$
- Magnetic force on segment of line  $b$ :  $F_{ab} = I_b L B_a$
- Magnetic force per unit length (attractive):  $\frac{F_{ab}}{L} = \frac{\mu_0 I_a I_b}{2\pi d}$



# Is There Absolute Motion?



Forces between two long, parallel, charged rods



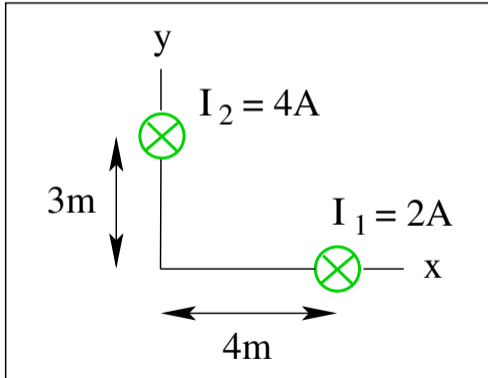
- $\frac{F_E}{L} = \frac{1}{2\pi\epsilon_0} \frac{\lambda_1\lambda_2}{d}$  (left),  $\frac{F_E^*}{L} = \frac{1}{2\pi\epsilon_0} \frac{\lambda_1^*\lambda_2^*}{d}$ ,  $\frac{F_B}{L} = \frac{\mu_0}{2\pi} \frac{I_1I_2}{d}$ , (right)
- $\frac{F_E^* - F_B}{L} = \frac{1}{2\pi\epsilon_0} \frac{\lambda_1^*\lambda_2^*}{d} \left(1 - \frac{v^2}{c^2}\right) = \frac{1}{2\pi\epsilon_0} \frac{\lambda_1\lambda_2}{d}$
- $c = \frac{1}{\sqrt{\epsilon_0\mu_0}} = 2.998 \times 10^8 \text{ms}^{-1}$  (speed of light)
- $\lambda_1^* = \frac{\lambda_1}{\sqrt{1 - v^2/c^2}}$ ,  $\lambda_2^* = \frac{\lambda_2}{\sqrt{1 - v^2/c^2}}$  (due to length contraction)





Consider two infinitely long straight currents  $I_1$  and  $I_2$  as shown.

- Find the components  $B_x$  and  $B_y$  of the magnetic field at the origin of the coordinate system.

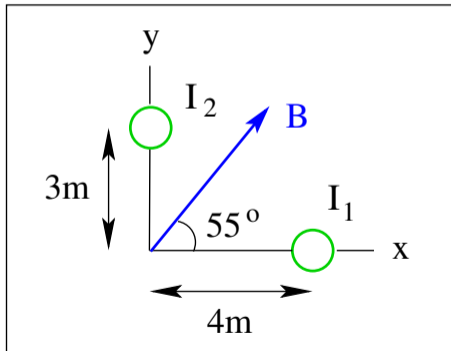


## Magnetic Field Application (13)



Two straight electric currents  $I_1$  and  $I_2$  of infinite length directed perpendicular to the  $xy$ -plane generate a magnetic field of magnitude  $B = 6.4 \times 10^{-7} \text{T}$  in the direction shown.

- Find the magnitude and direction ( $\odot, \otimes$ ) of each current.

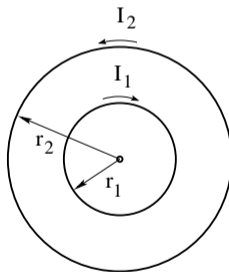




Consider two circular currents  $I_1 = 3\text{A}$  at radius  $r_1 = 2\text{m}$  and  $I_2 = 5\text{A}$  at radius  $r_2 = 4\text{m}$  in the directions shown.

(a) Find magnitude  $B$  and direction ( $\odot, \otimes$ ) of the resultant magnetic field at the center.

(b) Find magnitude  $\mu$  and direction ( $\odot, \otimes$ ) of the magnetic dipole moment generated by the two currents.





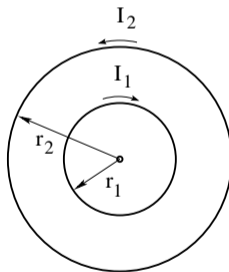
Consider two circular currents  $I_1 = 3\text{A}$  at radius  $r_1 = 2\text{m}$  and  $I_2 = 5\text{A}$  at radius  $r_2 = 4\text{m}$  in the directions shown.

(a) Find magnitude  $B$  and direction ( $\odot, \otimes$ ) of the resultant magnetic field at the center.

(b) Find magnitude  $\mu$  and direction ( $\odot, \otimes$ ) of the magnetic dipole moment generated by the two currents.

**Solution:**

$$\begin{aligned} \text{(a) } B &= \frac{\mu_0(3\text{A})}{2(2\text{m})} - \frac{\mu_0(5\text{A})}{2(4\text{m})} = (9.42 - 7.85) \times 10^{-7}\text{T} \\ \Rightarrow B &= 1.57 \times 10^{-7}\text{T} \quad \otimes \end{aligned}$$





Consider two circular currents  $I_1 = 3\text{A}$  at radius  $r_1 = 2\text{m}$  and  $I_2 = 5\text{A}$  at radius  $r_2 = 4\text{m}$  in the directions shown.

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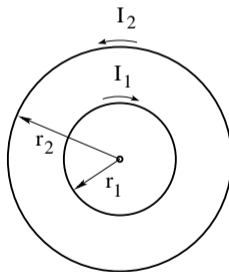
**Solution:**

$$(a) B = \frac{\mu_0(3\text{A})}{2(2\text{m})} - \frac{\mu_0(5\text{A})}{2(4\text{m})} = (9.42 - 7.85) \times 10^{-7}\text{T}$$

$$\Rightarrow B = 1.57 \times 10^{-7}\text{T} \quad \otimes$$

$$(b) \mu = \pi(4\text{m})^2(5\text{A}) - \pi(2\text{m})^2(3\text{A}) = (251 - 38)\text{Am}^2$$

$$\Rightarrow \mu = 213\text{Am}^2 \quad \odot$$

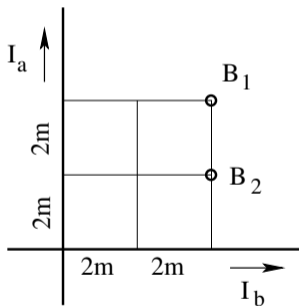


## Intermediate Exam III: Problem #1 (Spring '06)



Consider two infinitely long, straight wires with currents of equal magnitude  $I_1 = I_2 = 5\text{A}$  in the directions shown.

Find the direction (in/out) and the magnitude of the magnetic fields  $\mathbf{B}_1$  and  $\mathbf{B}_2$  at the points marked in the graph.

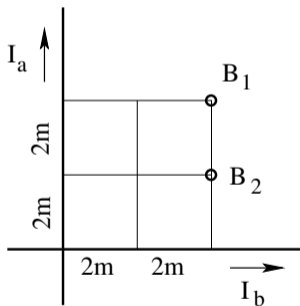


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**Solution:**

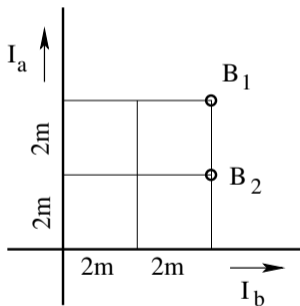
$$\bullet B_1 = \frac{\mu_0}{2\pi} \left( \frac{5\text{A}}{4\text{m}} - \frac{5\text{A}}{4\text{m}} \right) = 0 \quad (\text{no direction}).$$

## Intermediate Exam III: Problem #1 (Spring '06)



Consider two infinitely long, straight wires with currents of equal magnitude  $I_1 = I_2 = 5\text{A}$  in the directions shown.

Find the direction (in/out) and the magnitude of the magnetic fields  $\mathbf{B}_1$  and  $\mathbf{B}_2$  at the points marked in the graph.



**Solution:**

$$\bullet B_1 = \frac{\mu_0}{2\pi} \left( \frac{5\text{A}}{4\text{m}} - \frac{5\text{A}}{4\text{m}} \right) = 0 \quad (\text{no direction}).$$

$$\bullet B_2 = \frac{\mu_0}{2\pi} \left( \frac{5\text{A}}{2\text{m}} - \frac{5\text{A}}{4\text{m}} \right) = 0.25\mu\text{T} \quad (\text{out of plane}).$$

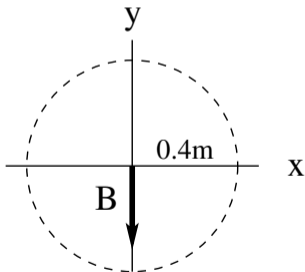


## Intermediate Exam III: Problem #1 (Spring '05)



An infinitely long straight current of magnitude  $I = 6\text{A}$  is directed into the plane ( $\otimes$ ) and located a distance  $d = 0.4\text{m}$  from the coordinate origin (somewhere on the dashed circle). The magnetic field  $\vec{B}$  generated by this current is in the negative  $y$ -direction as shown.

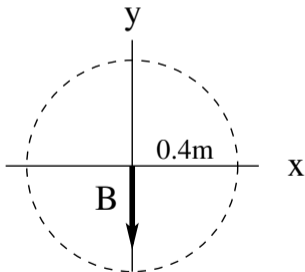
- Find the magnitude  $B$  of the magnetic field.
- Mark the location of the position of the current  $\otimes$  on the dashed circle.





An infinitely long straight current of magnitude  $I = 6\text{A}$  is directed into the plane ( $\otimes$ ) and located a distance  $d = 0.4\text{m}$  from the coordinate origin (somewhere on the dashed circle). The magnetic field  $\vec{B}$  generated by this current is in the negative  $y$ -direction as shown.

- (a) Find the magnitude  $B$  of the magnetic field.
- (b) Mark the location of the position of the current  $\otimes$  on the dashed circle.



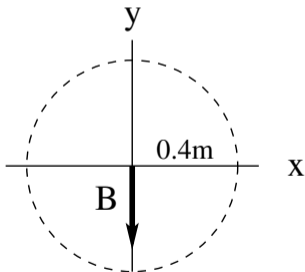
**Solution:**

(a)  $B = \frac{\mu_0 I}{2\pi d} = 3\mu\text{T}.$



An infinitely long straight current of magnitude  $I = 6\text{A}$  is directed into the plane ( $\otimes$ ) and located a distance  $d = 0.4\text{m}$  from the coordinate origin (somewhere on the dashed circle). The magnetic field  $\vec{B}$  generated by this current is in the negative  $y$ -direction as shown.

- Find the magnitude  $B$  of the magnetic field.
- Mark the location of the position of the current  $\otimes$  on the dashed circle.



**Solution:**

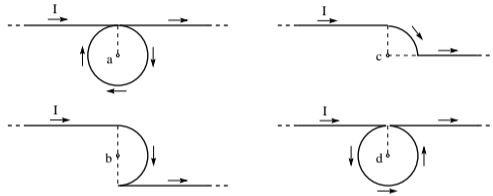
(a)  $B = \frac{\mu_0 I}{2\pi d} = 3\mu\text{T}.$

(b) Position of current  $\otimes$  is at  $y = 0, x = -0.4\text{m}.$

## Unit Exam III: Problem #2 (Spring '09)



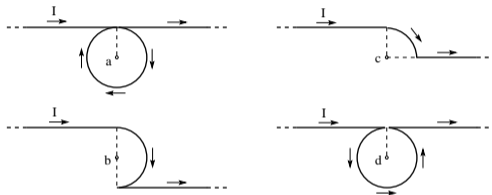
Two semi-infinite straight wires are connected to a curved wire in the form of a full circle, quarter circle, or half circle of radius  $R = 1\text{ m}$  in four different configurations. A current  $I = 1\text{ A}$  flows in the directions shown. Find magnitude  $B_a, B_b, B_c, B_d$  and direction ( $\odot/\otimes$ ) of the magnetic field thus generated at the points  $a, b, c, d$ .



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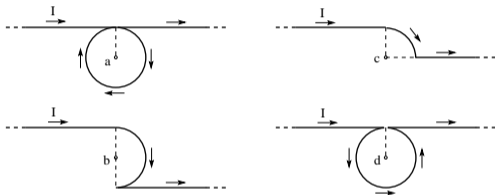
**Solution:**

$$B_a = \left| \frac{\mu_0 I}{4\pi R} + \frac{\mu_0 I}{2R} + \frac{\mu_0 I}{4\pi R} \right| = |100\text{nT} + 628\text{nT} + 100\text{nT}| = 828\text{nT} \quad \otimes$$

## Unit Exam III: Problem #2 (Spring '09)



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**Solution:**

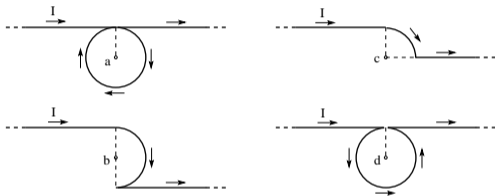
$$B_a = \left| \frac{\mu_0 I}{4\pi R} + \frac{\mu_0 I}{2R} + \frac{\mu_0 I}{4\pi R} \right| = |100\text{nT} + 628\text{nT} + 100\text{nT}| = 828\text{nT} \quad \otimes$$

$$B_b = \left| \frac{\mu_0 I}{4\pi R} + \frac{\mu_0 I}{4R} - \frac{\mu_0 I}{4\pi R} \right| = |100\text{nT} + 314\text{nT} - 100\text{nT}| = 314\text{nT} \quad \otimes$$

## Unit Exam III: Problem #2 (Spring '09)



Two semi-infinite straight wires are connected to a curved wire in the form of a full circle, quarter circle, or half circle of radius  $R = 1\text{m}$  in four different configurations. A current  $I = 1\text{A}$  flows in the directions shown. Find magnitude  $B_a, B_b, B_c, B_d$  and direction ( $\odot/\otimes$ ) of the magnetic field thus generated at the points  $a, b, c, d$ .



**Solution:**

$$B_a = \left| \frac{\mu_0 I}{4\pi R} + \frac{\mu_0 I}{2R} + \frac{\mu_0 I}{4\pi R} \right| = |100\text{nT} + 628\text{nT} + 100\text{nT}| = 828\text{nT} \quad \otimes$$

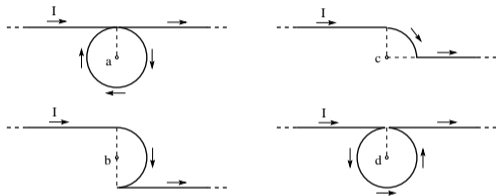
$$B_b = \left| \frac{\mu_0 I}{4\pi R} + \frac{\mu_0 I}{4R} - \frac{\mu_0 I}{4\pi R} \right| = |100\text{nT} + 314\text{nT} - 100\text{nT}| = 314\text{nT} \quad \otimes$$

$$B_c = \left| \frac{\mu_0 I}{4\pi R} + \frac{\mu_0 I}{8R} + 0 \right| = |100\text{nT} + 157\text{nT}| = 257\text{nT} \quad \otimes$$

## Unit Exam III: Problem #2 (Spring '09)



Two semi-infinite straight wires are connected to a curved wire in the form of a full circle, quarter circle, or half circle of radius  $R = 1\text{m}$  in four different configurations. A current  $I = 1\text{A}$  flows in the directions shown. Find magnitude  $B_a, B_b, B_c, B_d$  and direction ( $\odot/\otimes$ ) of the magnetic field thus generated at the points  $a, b, c, d$ .



**Solution:**

$$B_a = \left| \frac{\mu_0 I}{4\pi R} + \frac{\mu_0 I}{2R} + \frac{\mu_0 I}{4\pi R} \right| = |100\text{nT} + 628\text{nT} + 100\text{nT}| = 828\text{nT} \quad \otimes$$

$$B_b = \left| \frac{\mu_0 I}{4\pi R} + \frac{\mu_0 I}{4R} - \frac{\mu_0 I}{4\pi R} \right| = |100\text{nT} + 314\text{nT} - 100\text{nT}| = 314\text{nT} \quad \otimes$$

$$B_c = \left| \frac{\mu_0 I}{4\pi R} + \frac{\mu_0 I}{8R} + 0 \right| = |100\text{nT} + 157\text{nT}| = 257\text{nT} \quad \otimes$$

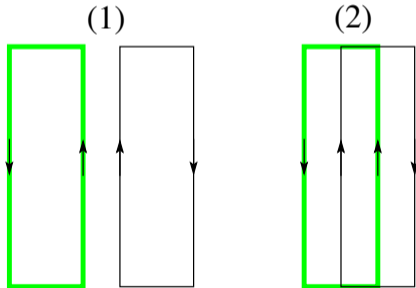
$$B_d = \left| \frac{\mu_0 I}{4\pi R} - \frac{\mu_0 I}{2R} + \frac{\mu_0 I}{4\pi R} \right| = |100\text{nT} - 628\text{nT} + 100\text{nT}| = 428\text{nT} \quad \odot$$





Consider two pairs of rectangular electric currents flowing in the directions indicated.

- (a) What is the direction ( $\rightarrow$ ,  $\leftarrow$ ) of the magnetic force experienced by the black rectangle in each case?
- (b) Which black rectangle experiences the stronger magnetic force?

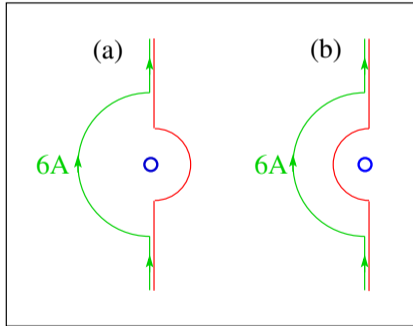


# Magnetic Field Application (9)



Two wires of infinite length contain concentric semicircular segments of radii 1m and 2m, respectively.

- If one of the wires carries a 6A current in the direction indicated, what must be the direction ( $\uparrow, \downarrow$ ) and magnitude of the current in the other wire such that the magnetic field at the center of the semicircles vanishes?





The currents  $I_1, I_2$  in two long straight wires have equal magnitude and generate a magnetic field  $\vec{B}$  as shown at three points in space.

- Find the directions ( $\odot, \otimes$ ) for  $I_1, I_2$  in configurations (a) and (b).

