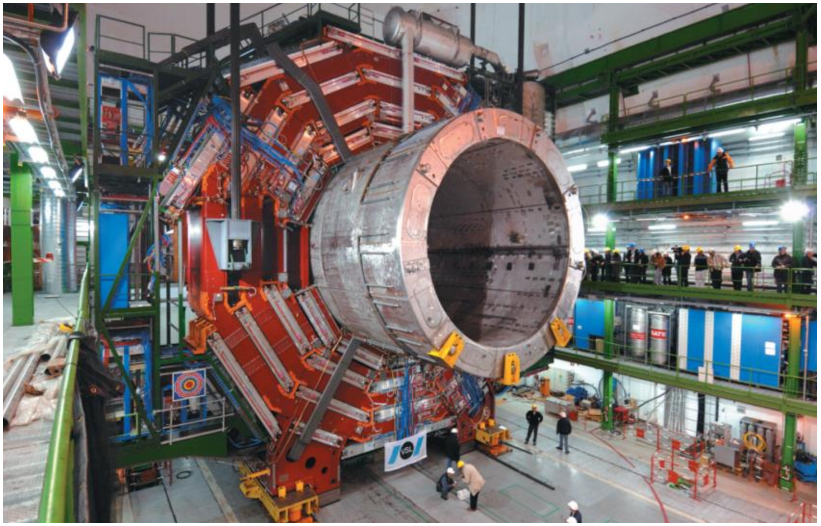
Chp 28: Sources of Magnetic Field - (I)

Goals for Chapter 28

- To determine the magnetic field produced by a moving charge
- To study the magnetic field of an element of a current-carrying conductor
- To calculate the magnetic field of a long, straight, current-carrying conductor
- To study the magnetic force between current- carrying wires
- To determine the magnetic field of a circular loop
- To use Ampere's Law to calculate magnetic fields

Introduction



Compact Muon Solenoid detector
(CMS experiment)

Previously we studied a charged particle (or current) in a magnetic field (B).

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

$$d\vec{F} = I\, d\vec{l} \times \vec{B}$$

- What actually creates magnetic fields?
- What can we say about the magnetic field due to a solenoid?
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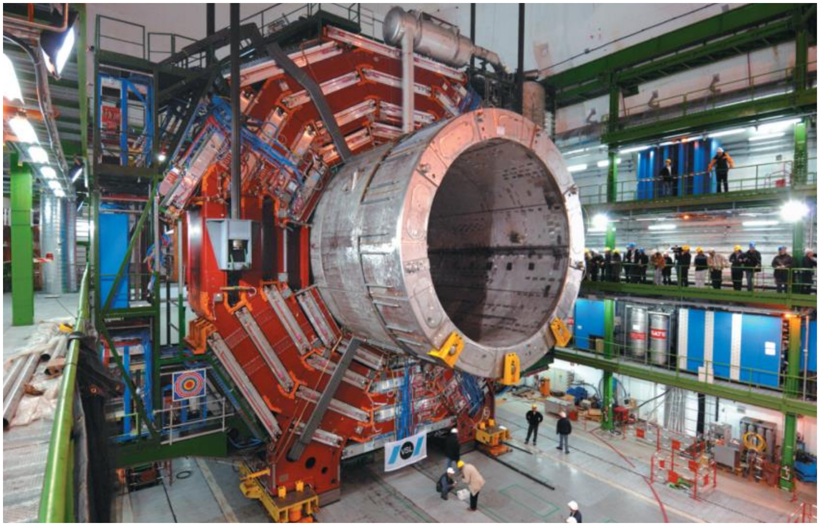

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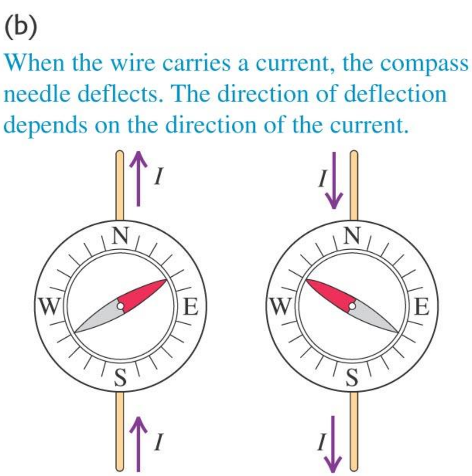
Magnetic Field of a Moving Charge

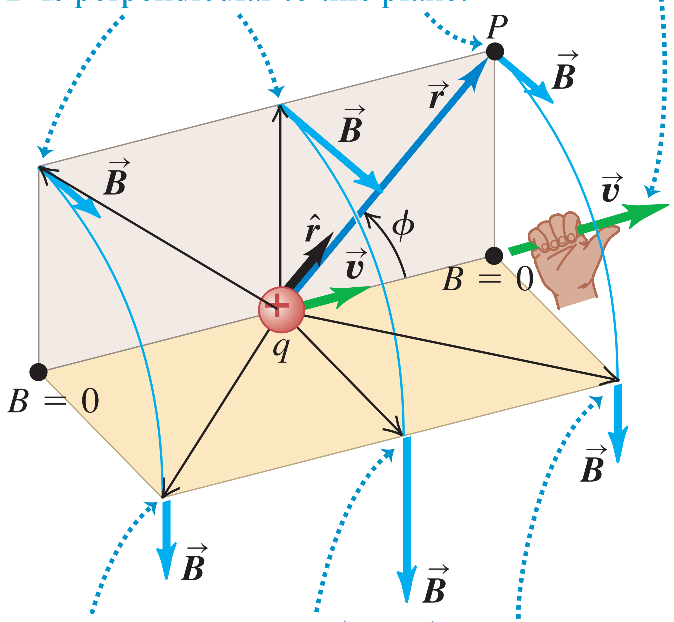


the *electric* field ***E*** caused by the charge is proportional to the charge magnitude q and to $1/r^2$. The corresponding relationship for the *magnetic* field ***B*** of a point charge q moving with constant velocity has some similarities and some interesting differences.

The magnetic field of a moving charge

Right-hand rule for the magnetic field due to a positive charge moving at constant velocity: Point the thumb of your right hand in the direction of the velocity. Your fingers now curl around the charge in the direction of the magnetic field lines. (If the charge is negative, the field lines are in the opposite direction.)

For these field points, $\vec{r}$ and $\vec{v}$ both lie in the beige plane, and $\vec{B}$ is perpendicular to this plane.



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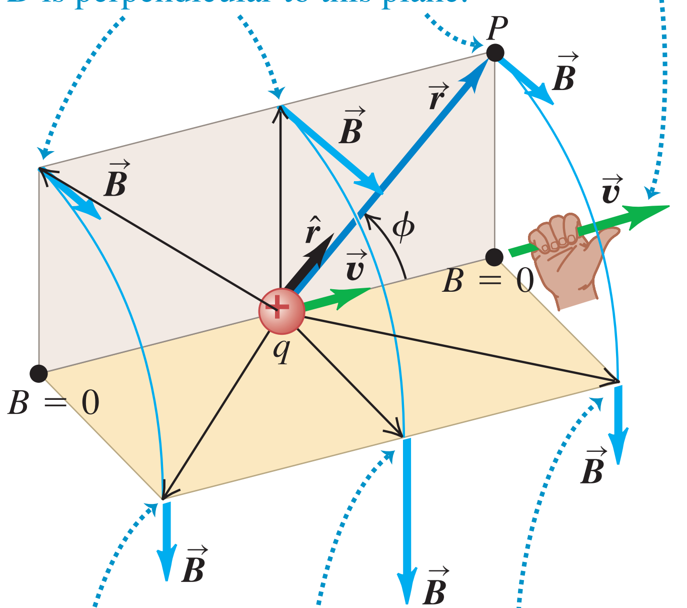

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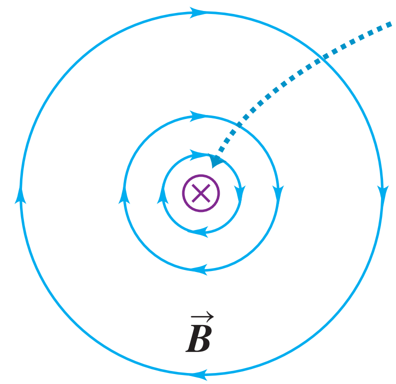
$$\vec{B} = \frac{\mu_0}{4\pi}\frac{q\vec{v} \times \hat{r}}{r^2}$$ (magnetic field of a point charge with constant velocity)

(b) View from behind the charge



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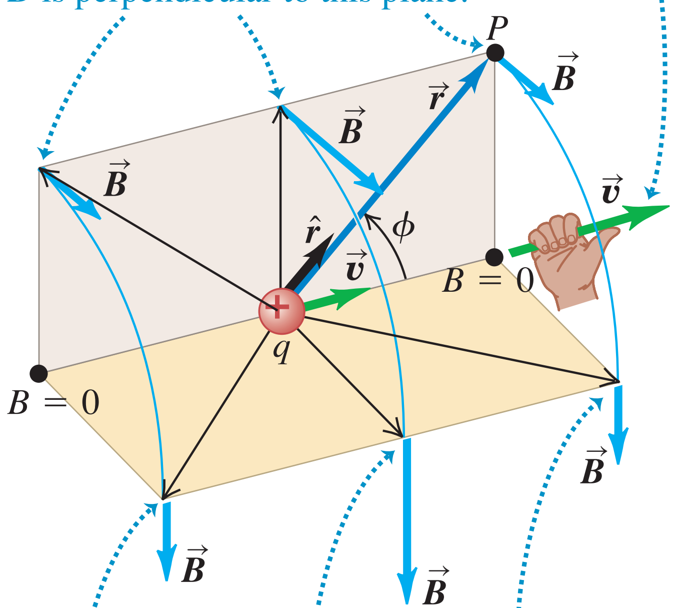

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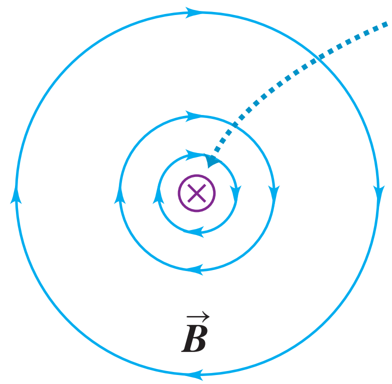

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$$1\ \text{T} = 1\ \text{N}\cdot\text{s/C}\cdot\text{m} = 1\ \text{N/A}\cdot\text{m}$$

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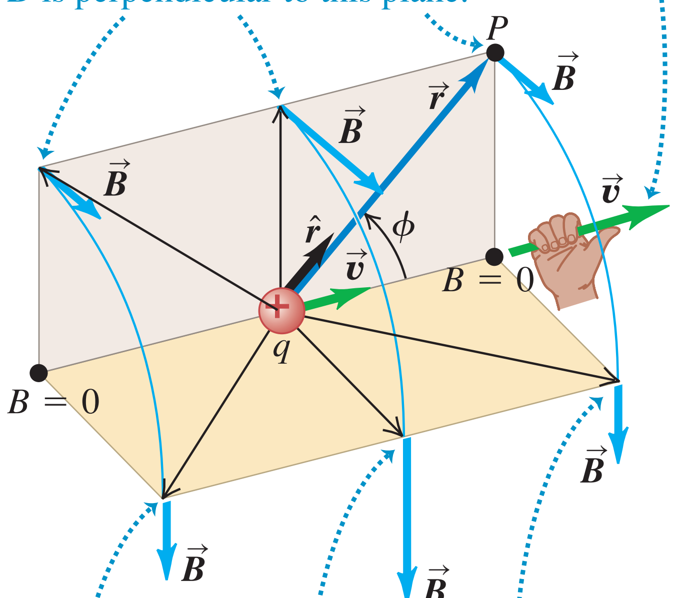

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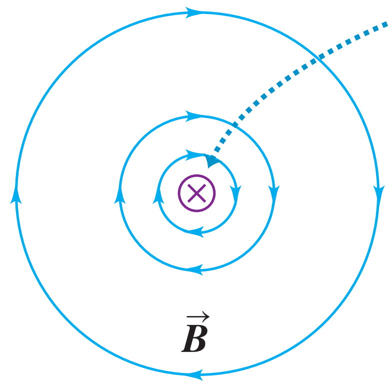

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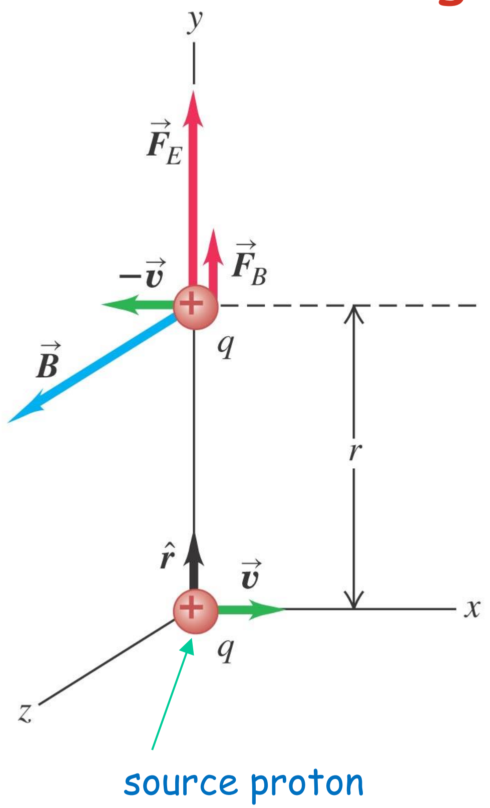
$$k = \frac{1}{4\pi\epsilon_0} = (10^{-7}\ \mathrm{N \cdot s^2/C^2})c^2$$

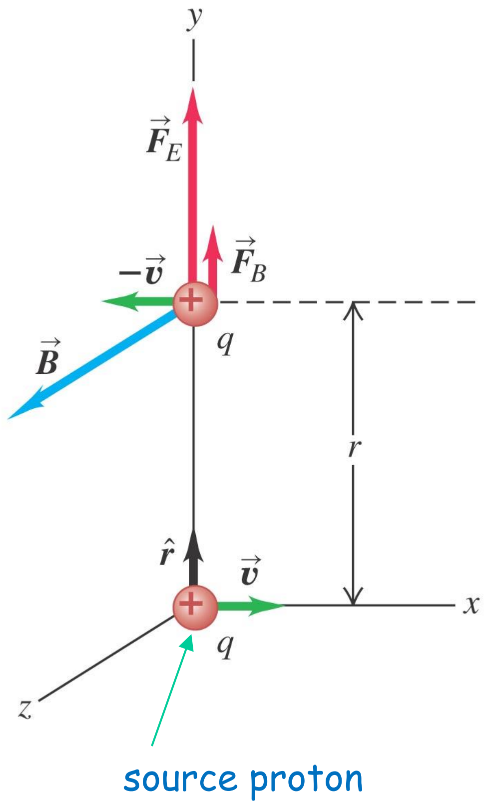
$$c^2 = \frac{1}{\epsilon_0\mu_0}$$

Where speed of light
$C = 3.10^8$ m/s

Magnetic force between moving protons



Forces between moving protons



From Coulomb's law, the magnitude of the electric force on the upper proton is

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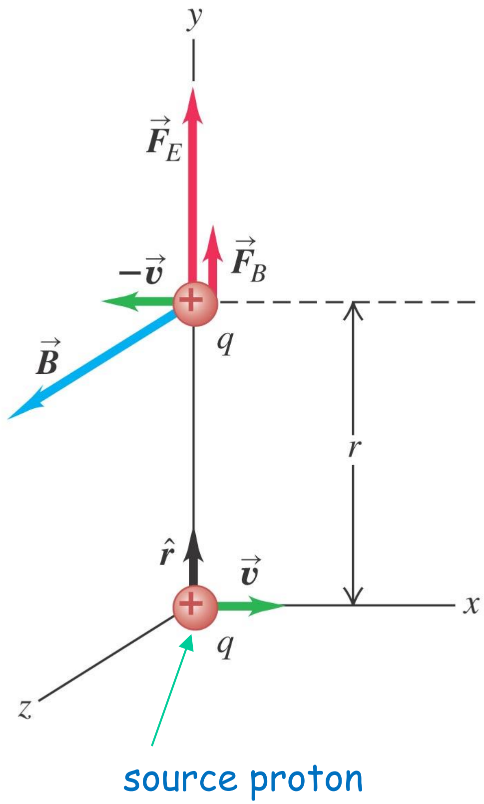

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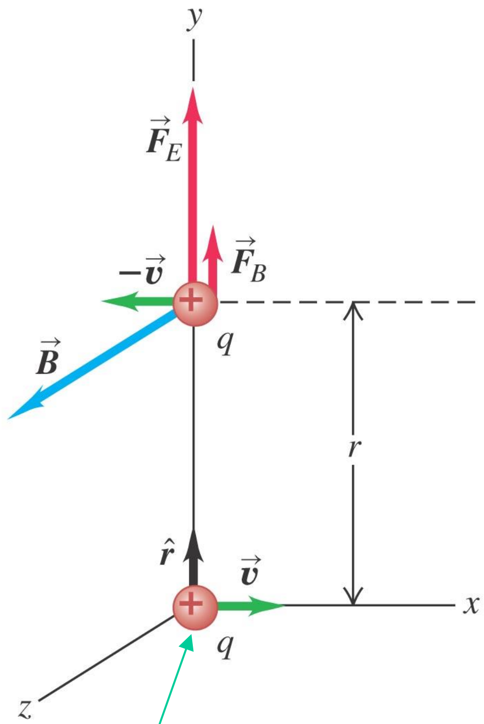

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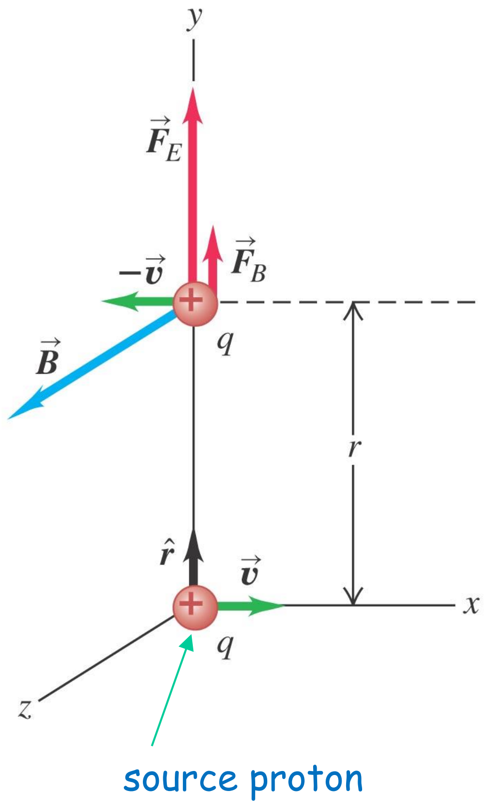

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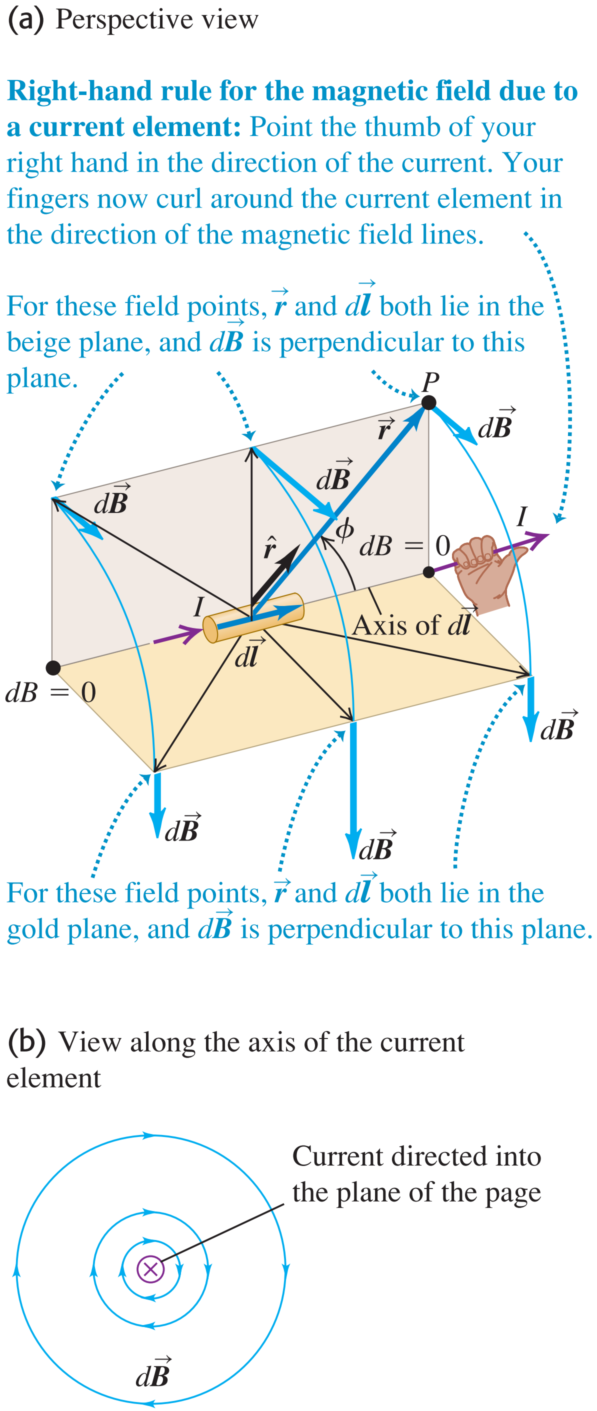
$$\frac{F_B}{F_E} = \frac{\mu_0 q^2v^2/4\pi r^2}{q^2/4\pi\epsilon_0 r^2} = \frac{\mu_0 v^2}{1/\epsilon_0} = \epsilon_0\mu_0 v^2$$

$$\epsilon_0\mu_0 = 1/c^2 \quad \Rightarrow \quad \frac{F_B}{F_E} = \frac{v^2}{c^2}$$

Magnetic field of a current element



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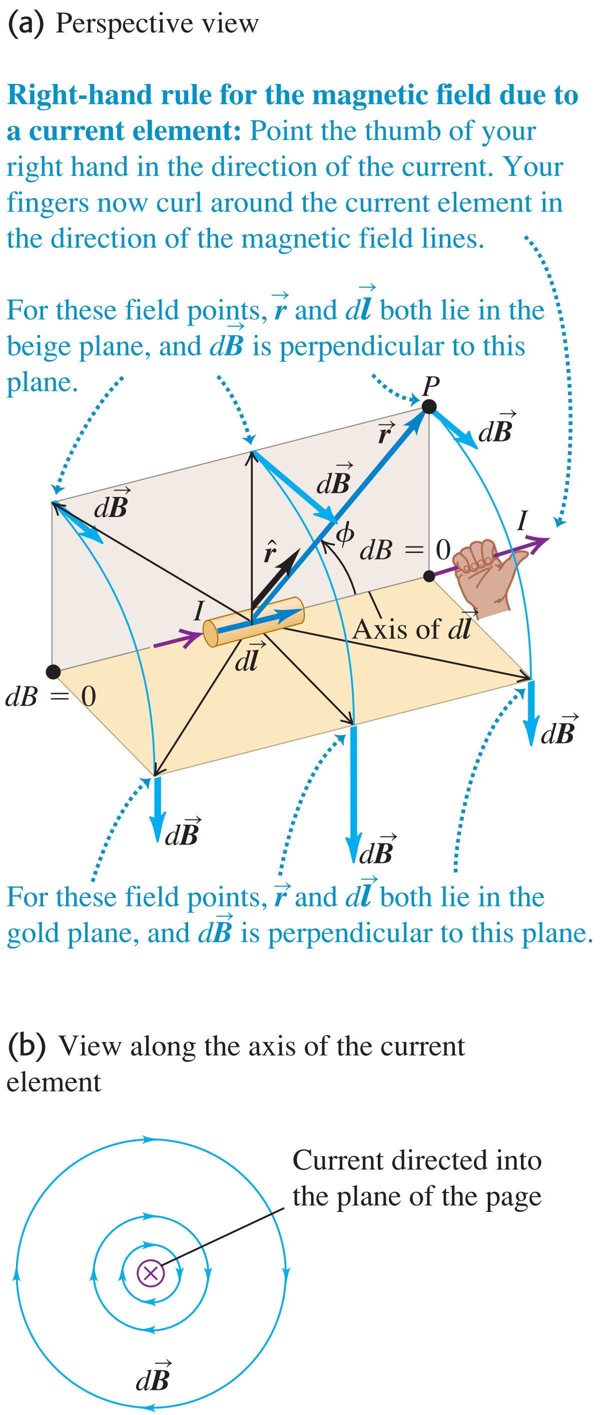

The total magnetic field caused by several moving charges is the vector sum of the fields caused by the individual charges.
If there are n moving charged particles per unit volume, each of charge q, the total moving charge dQ in the segment is

$$dQ = nqA\,dl$$

Magnetic field of a current element

(a) Perspective view

Right-hand rule for the magnetic field due to a current element: Point the thumb of your right hand in the direction of the current. Your fingers now curl around the current element in the direction of the magnetic field lines.

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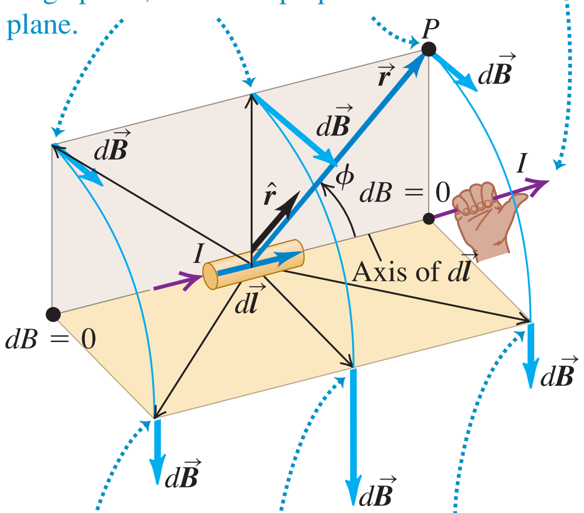

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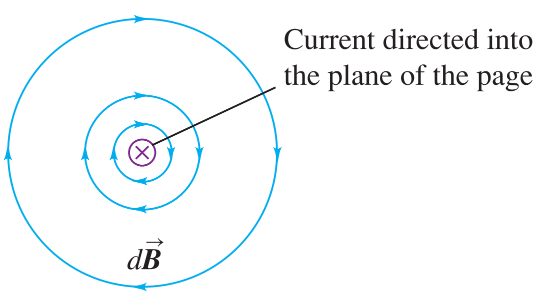
(b) View along the axis of the current element



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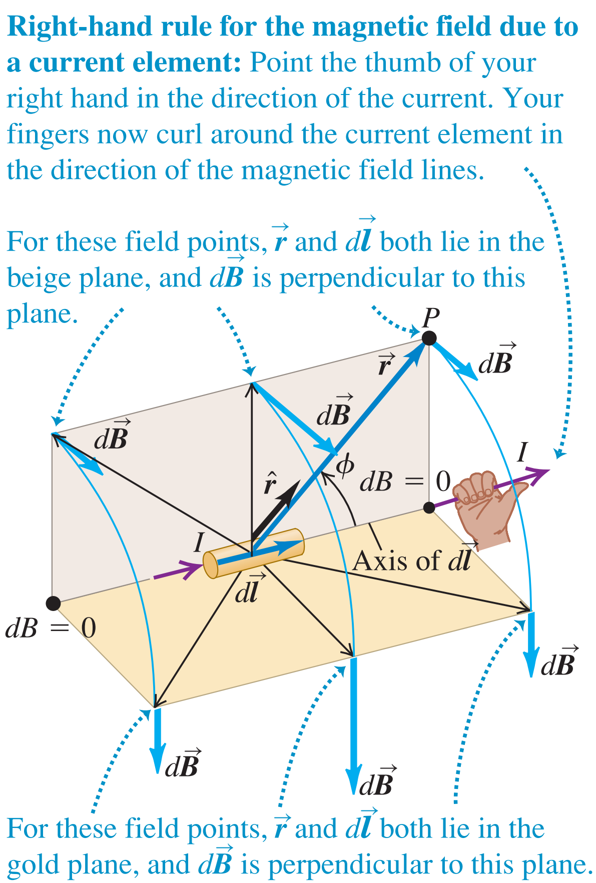

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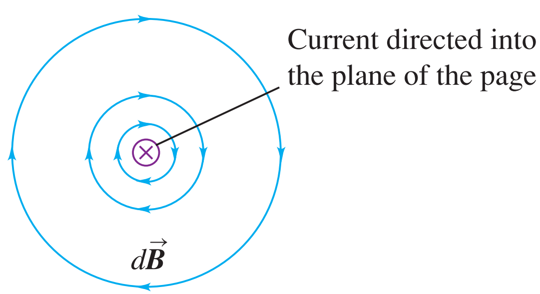

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$N|q|v_d A$ equals the current I in the element.

$$\Rightarrow \quad dB = \frac{\mu_0}{4\pi}\frac{I\,dl \sin\phi}{r^2}$$

$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{I\,d\vec{l} \times \hat{r}}{r^2} \qquad \text{(magnetic field of a current element)}$$

Biot and Savart law (pro- nounced "Bee-oh" and "Suh-var")

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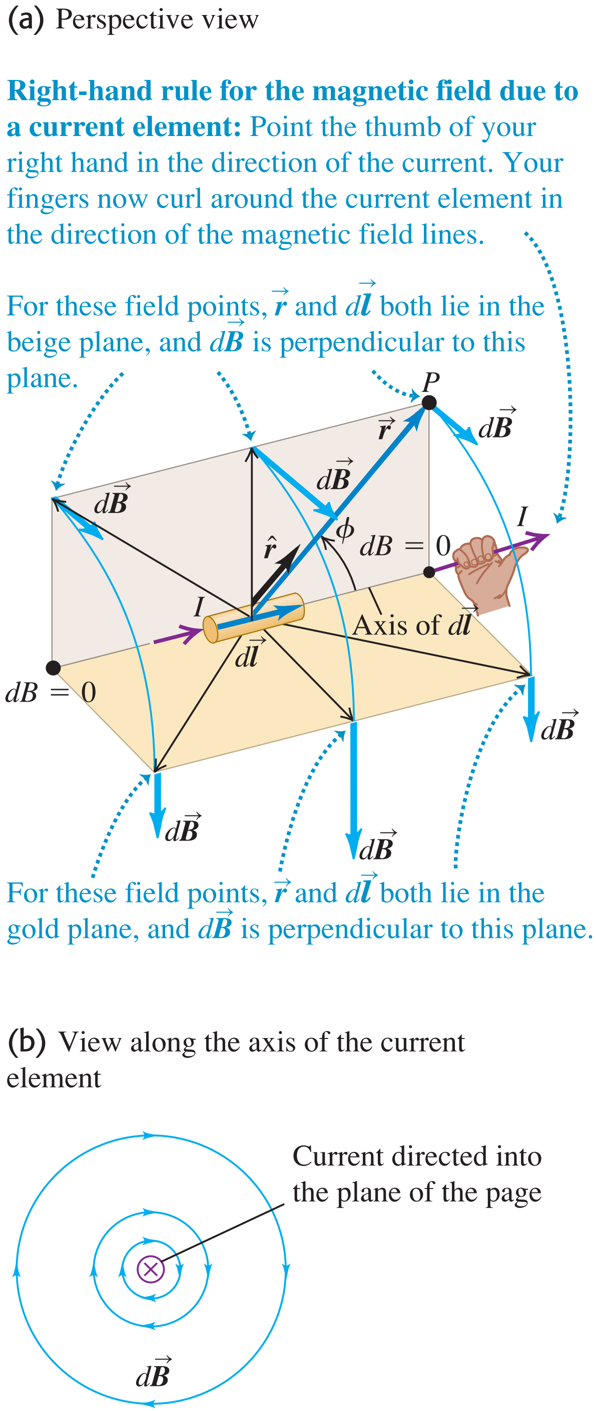

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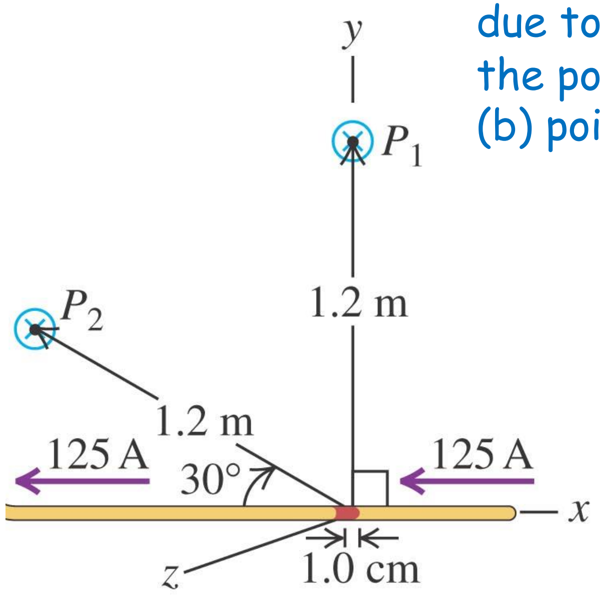
$$\vec{B} = \frac{\mu_0}{4\pi}\int \frac{I\,d\vec{l} \times \hat{r}}{r^2}$$

Ex: Magnetic field of a current segment



A copper wire carries a steady 125-A current.Find the magnetic field due to a 1.0-cm segment of this wire at a point 1.2 m away from it, if the point is (a) point P_1, straight out to the side of the segment, and (b) point P_2, in the xy-plane and on a line at 30° to the segment.

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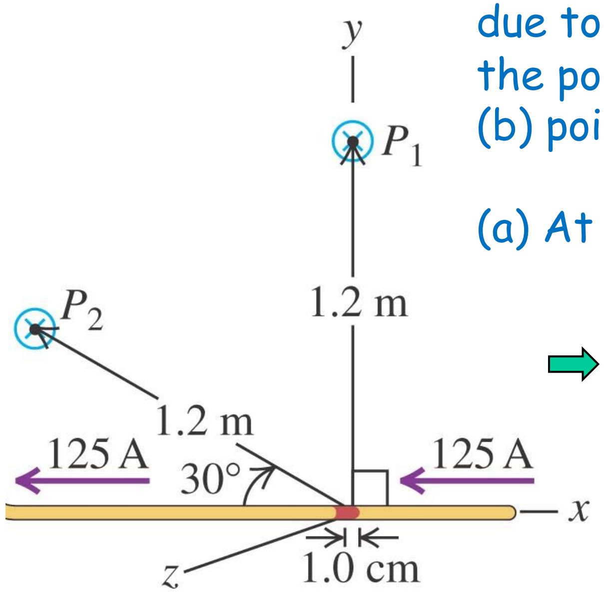

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(a) At point P_1 $\hat{\boldsymbol{r}}_1 = \hat{\boldsymbol{j}}$

$$\vec{\boldsymbol{B}} = \frac{\mu_0}{4\pi}\frac{I\,d\vec{\boldsymbol{l}} \times \hat{\boldsymbol{r}}}{r^2} = \frac{\mu_0}{4\pi}\frac{I\,dl(-\hat{\boldsymbol{\imath}}) \times \hat{\boldsymbol{j}}}{r^2} = -\frac{\mu_0}{4\pi}\frac{I\,dl}{r^2}\hat{\boldsymbol{k}}$$

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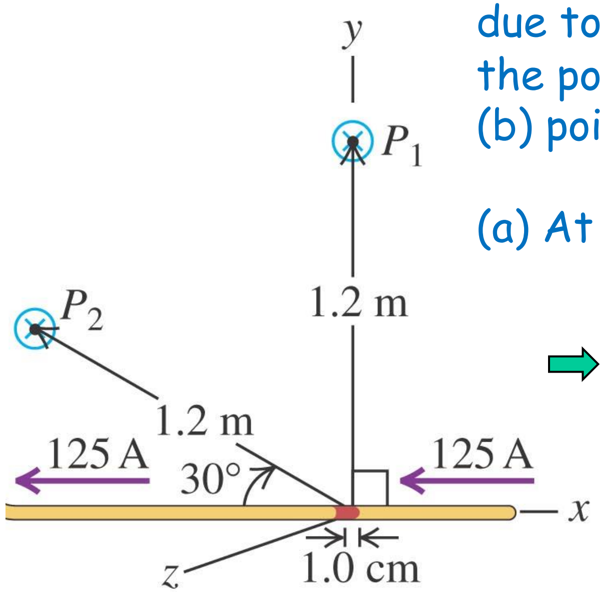

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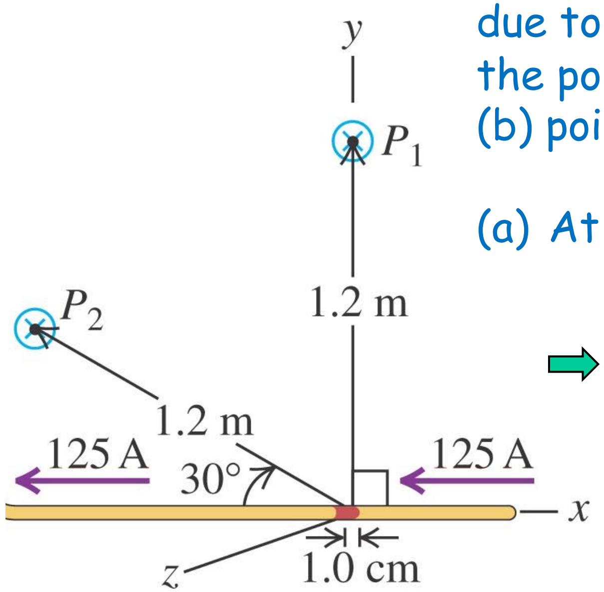

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$\hat{\boldsymbol{r}} = (-\cos 30°)\hat{\boldsymbol{\imath}} + (\sin 30°)\hat{\boldsymbol{\jmath}}$

(b) At point P_2 $\hat{\boldsymbol{r}}_1 = \hat{\boldsymbol{j}}$

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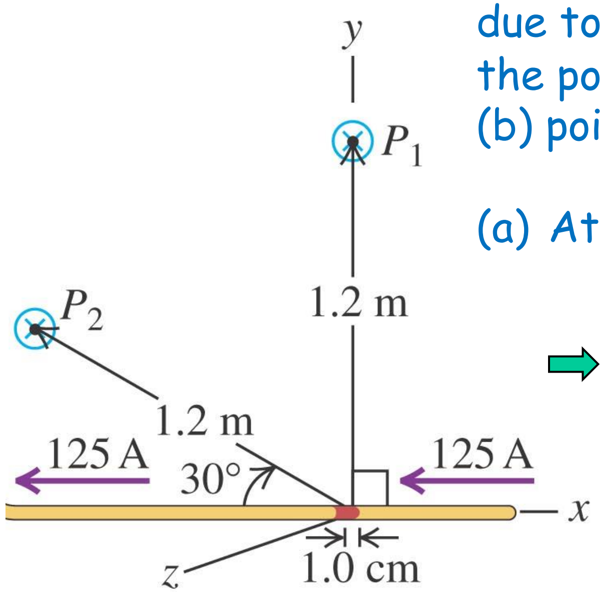

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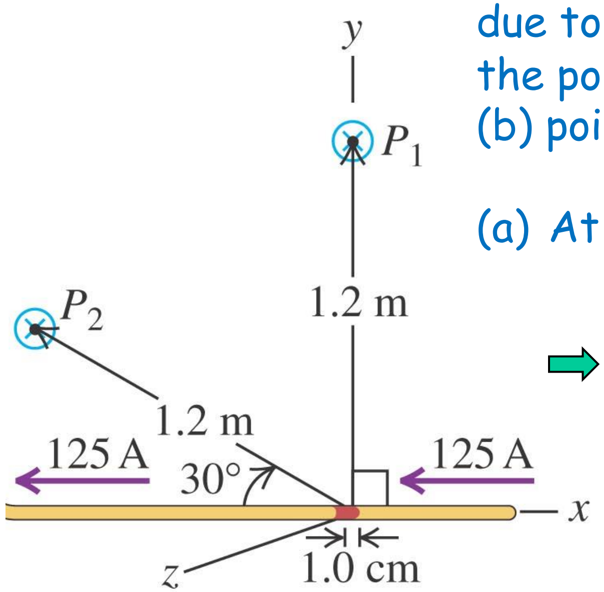
$$\vec{\boldsymbol{B}} = \frac{\mu_0}{4\pi}\frac{I\,d\vec{\boldsymbol{l}} \times \hat{\boldsymbol{r}}}{r^2} = \frac{\mu_0}{4\pi}\frac{I\,dl(-\hat{\boldsymbol{\imath}}) \times (-\cos 30°\hat{\boldsymbol{\imath}} + \sin 30°\hat{\boldsymbol{\jmath}})}{r^2} = -\frac{\mu_0 I}{4\pi}\frac{dl\sin 30°}{r^2}\hat{\boldsymbol{k}}$$

Ex: Magnetic field of a current segment



A copper wire carries a steady 125-A current.Find the magnetic field due to a 1.0-cm segment of this wire at a point 1.2 m away from it, if the point is (a) point P_1, straight out to the side of the segment, and (b) point P_2, in the xy-plane and on a line at 30° to the segment.

(a) At point P_1 $\hat{\boldsymbol{r}}_1 = \hat{\boldsymbol{j}}$

$$\vec{B} = \frac{\mu_0}{4\pi}\frac{I\,d\vec{l} \times \hat{r}}{r^2} = \frac{\mu_0}{4\pi}\frac{I\,dl(-\hat{\imath}) \times \hat{\jmath}}{r^2} = -\frac{\mu_0}{4\pi}\frac{I\,dl}{r^2}\hat{k}$$

$$= -(10^{-7}\ \mathrm{T \cdot m/A})\frac{(125\ \mathrm{A})(1.0 \times 10^{-2}\ \mathrm{m})}{(1.2\ \mathrm{m})^2}\hat{k} = -(8.7 \times 10^{-8}\ \mathrm{T})\hat{k}$$

$\hat{r} = (-\cos 30°)\hat{\imath} + (\sin 30°)\hat{\jmath}$

(b) At point P_2 $\hat{\boldsymbol{r}}_1 = \hat{\boldsymbol{j}}$

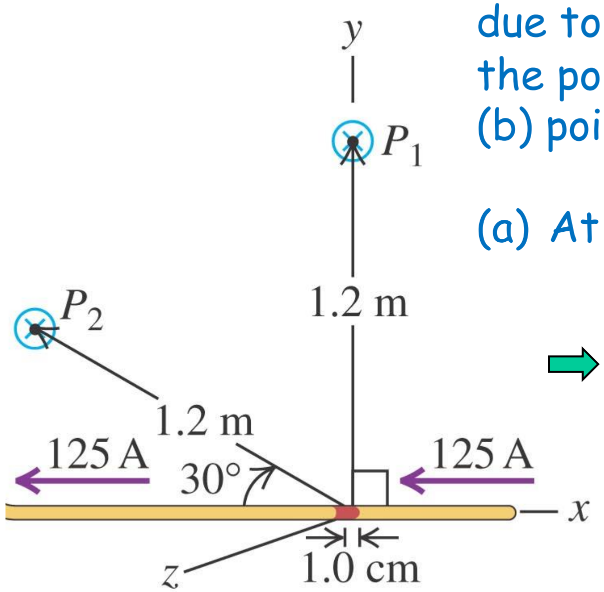
$$\hat{r} = (-\cos 30°)\hat{\imath} + (\sin 30°)\hat{\jmath}$$

$$\vec{B} = \frac{\mu_0}{4\pi}\frac{I\,d\vec{l} \times \hat{r}}{r^2} = \frac{\mu_0}{4\pi}\frac{I\,dl(-\hat{\imath}) \times (-\cos 30°\hat{\imath} + \sin 30°\hat{\jmath})}{r^2}$$

$$\vec{B} = \frac{\mu_0}{4\pi}\frac{I\,d\vec{l} \times \hat{r}}{r^2} = \frac{\mu_0}{4\pi}\frac{I\,dl(-\hat{\imath}) \times (-\cos 30°\hat{\imath} + \sin 30°\hat{\jmath})}{r^2} = -\frac{\mu_0 I}{4\pi}\frac{dl \sin 30°}{r^2}\hat{k}$$

$$= -(10^{-7}\ \mathrm{T \cdot m/A})\frac{(125\ \mathrm{A})(1.0 \times 10^{-2}\ \mathrm{m})(\sin 30°)}{(1.2\ \mathrm{m})^2}\hat{k} = -(4.3 \times 10^{-8}\ \mathrm{T})\hat{k}$$

Ex: Magnetic field of a current segment



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$\hat{r} = (-\cos 30°)\hat{\imath} + (\sin 30°)\hat{\jmath}$

(b) At point P_2 $\hat{\boldsymbol{r}}_1 = \hat{\boldsymbol{j}}$

$\hat{r} = (-\cos 30°)\hat{\imath} + (\sin 30°)\hat{\jmath}$

$$\vec{B} = \frac{\mu_0}{4\pi}\frac{I\,d\vec{l} \times \hat{r}}{r^2} = \frac{\mu_0}{4\pi}\frac{I\,dl(-\hat{\imath}) \times (-\cos 30°\hat{\imath} + \sin 30°\hat{\jmath})}{r^2}$$

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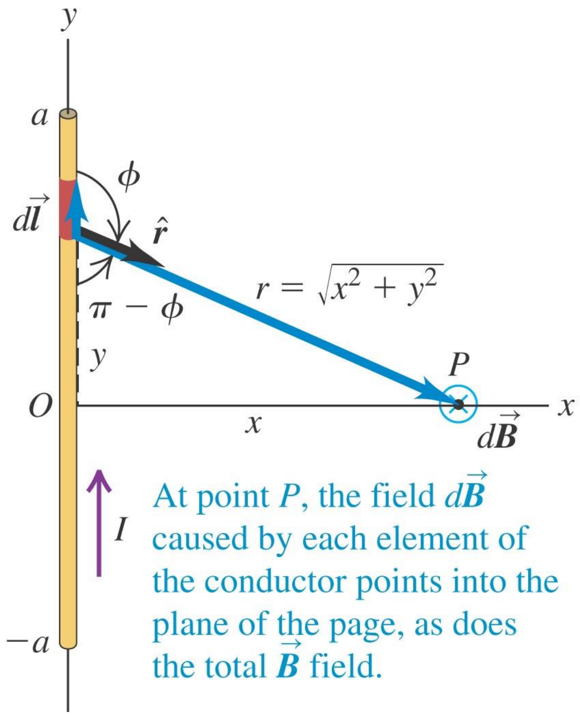
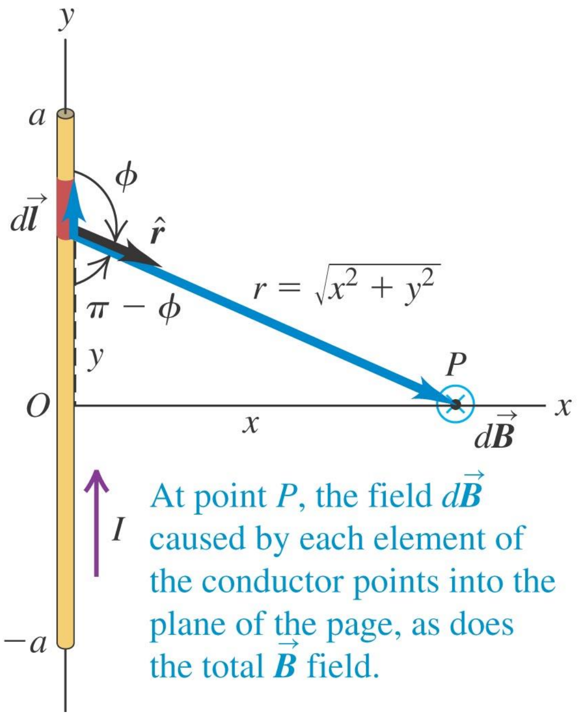
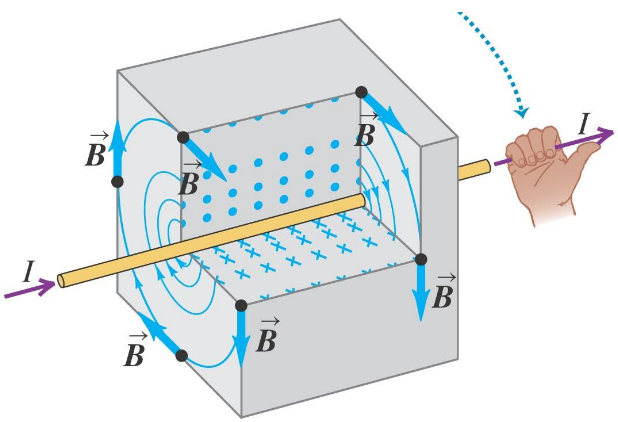
Directions inside the xy plane in both case.

Magnetic field of a straight current-carrying conductor

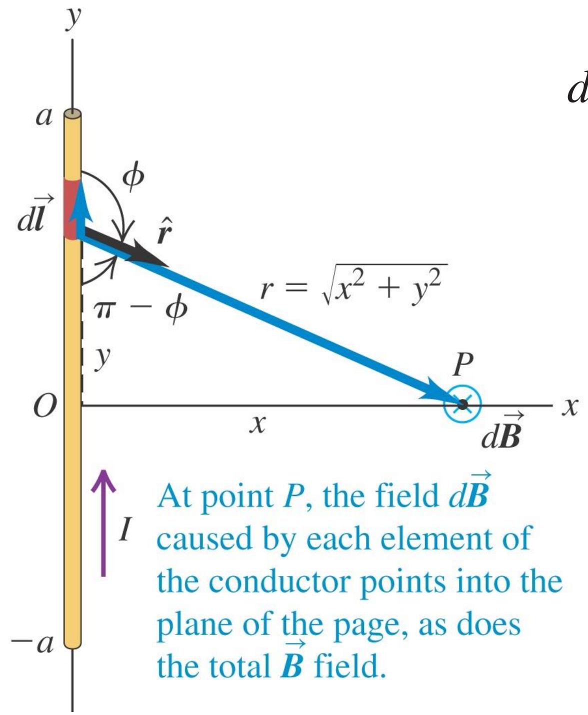


Magnetic field of a straight current-carrying conductor



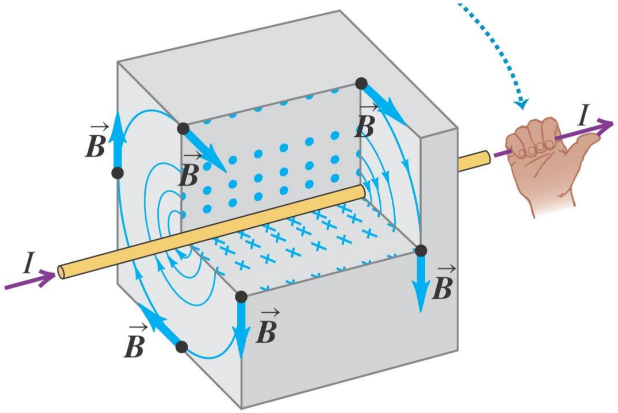


Magnetic field of a straight current-carrying conductor

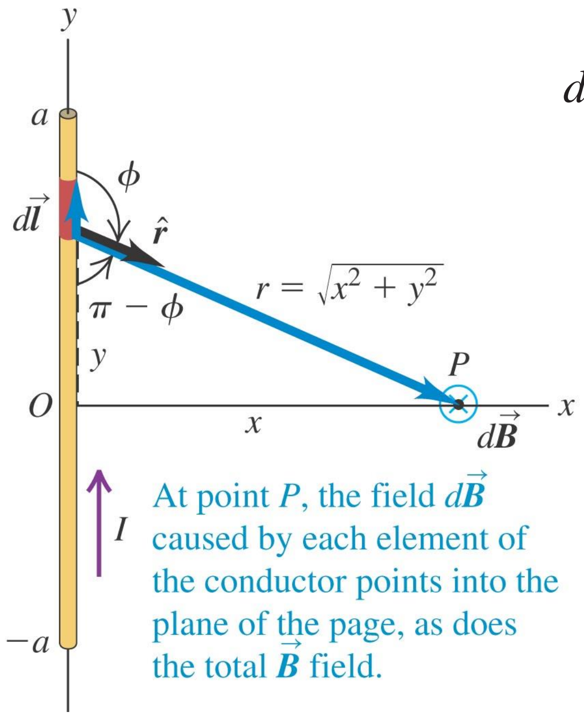


$$dB = \frac{\mu_0}{4\pi}\frac{I\,dl\sin\phi}{r^2}$$

$$\sin\phi = \sin(\pi - \phi) = x/\sqrt{x^2 + y^2}$$

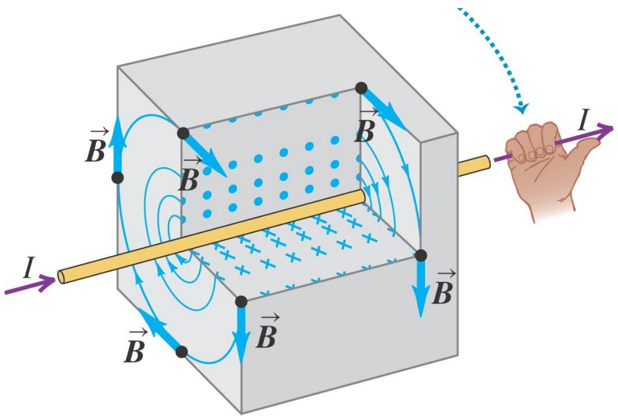


Magnetic field of a straight current-carrying conductor

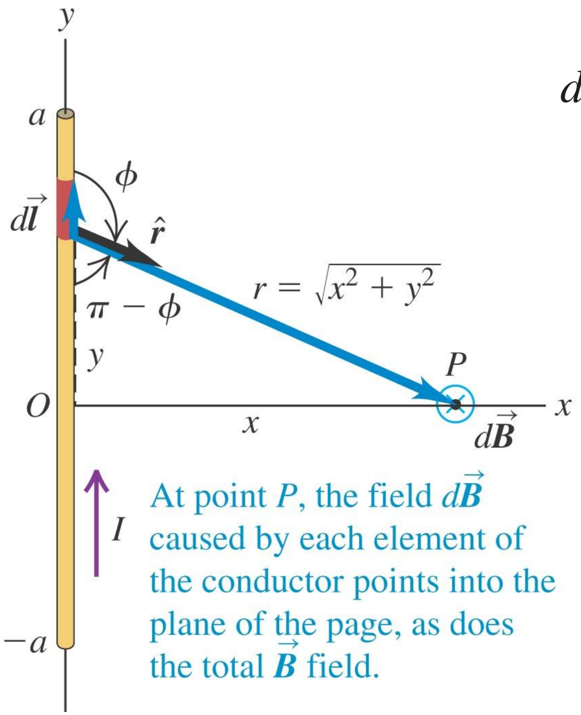


$$dB = \frac{\mu_0}{4\pi}\frac{I\,dl\sin\phi}{r^2} \qquad \sin\phi = \sin(\pi - \phi) = x/\sqrt{x^2 + y^2}$$

$$\Rightarrow \quad B = \frac{\mu_0 I}{4\pi}\int_{-a}^{a}\frac{x\,dy}{(x^2 + y^2)^{3/2}} = \frac{\mu_0 I}{4\pi}\frac{2a}{x\sqrt{x^2 + a^2}}$$



Magnetic field of a straight current-carrying conductor



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If a>>x (infinite line)

$$\Rightarrow \quad B = \frac{\mu_0 I}{2\pi x}$$