University of Science and Technology

Faculty of Computer Science and Information Technology

Course Handbook

Physics II

Course Coordinator

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Lecture six

Sources of Magnetic Fields

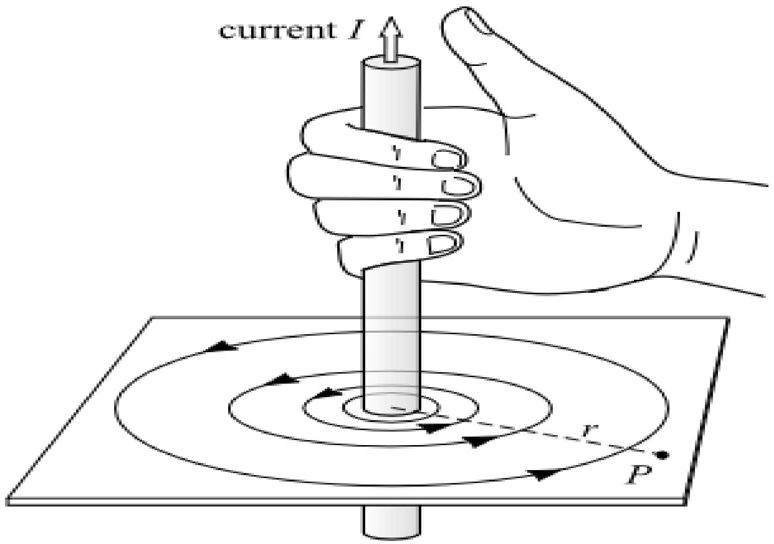
Sources of Magnetic Fields

MAGNETIC FIELDS ARE PRODUCED by moving charges, and of course that includes electric currents. Figure 31-1 shows the nature of the magnetic fields produced by several current configurations. Below each is given the value of B at the indicated point P. The constant $\mu_0 = 4\pi \times 10^{-7}\,\mathrm{T \cdot m/A}$ is called the *permeability of free space*. It is assumed that the surrounding material is vacuum or air.

THE DIRECTION OF THE MAGNETIC FIELD of a current-carrying wire can be found by using a right-hand rule, as illustrated in Fig. 31-1(*a*):

> Grasp the wire in the right hand, with the thumb pointing in the direction of the current. The fingers then circle the wire in the same direction as the magnetic field does.

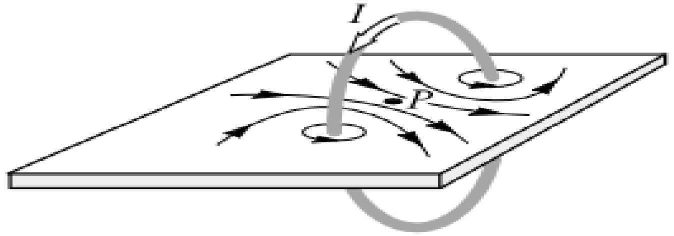
This same rule can be used to find the direction of the field for a current loop such as that shown in Fig. 31-1(*b*).



(a) Long straight wire:

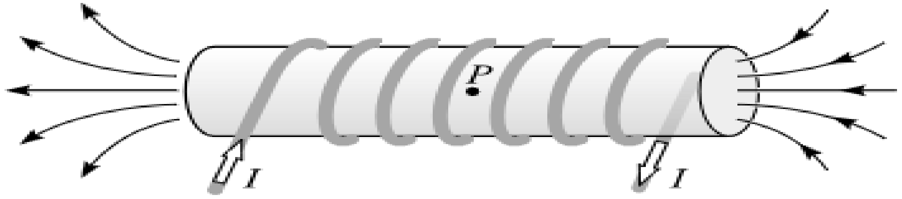
$$B = \frac{\mu_0 I}{2\pi r}$$

where r is distance to P from the axis of the wire



(b) Center of a circular coil with radius a and N loops:

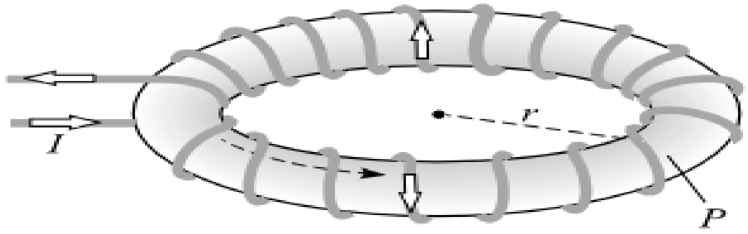
$$B = \frac{\mu_0 N I}{2a}$$



(c) Interior point of long solenoid with n loops per meter:

$$B = \mu_0 n I$$

It is constant in the interior



(d) Interior point of toroid having N loops:

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

where r is the radius of the circle on which P lies

Fig. 31-1

THE MAGNITUDE OF THE FORCE (F) on a charge moving in a magnetic field depends upon the product of four factors:

(1) q, the charge (in C)

(2) v, the magnitude of the velocity of the charge (in m/s)

(3) B, the strength of the magnetic field

(4) $\sin \theta$, where θ is the angle between the field lines and the velocity $\vec{\mathbf{v}}$.

THE MAGNETIC FIELD AT A POINT is represented by a vector $\vec{\mathbf{B}}$ that is variously called the *magnetic induction*, the *magnetic flux density*, or simply the *magnetic field*.

We define the magnitude of $\vec{\mathbf{B}}$ and its units by way of the equation

$$F_M = qvB \sin \theta$$

where F_M is in newtons, q is in coulombs, v is in m/s, and B is the magnetic field in a unit called the *tesla* (T). For reasons we will see later, a tesla is also expressed as a *weber per square meter*: $1 \text{ T} = 1 \text{ Wb/m}^2$ (see Chapter 32). Still encountered is the cgs unit for B, the *gauss* (G), where

$$1 \text{ G} = 10^{-4} \text{ T}$$

The Earth's magnetic field is a few tenths of a gauss. Also note that

$$1 \text{ T} = 1 \text{ Wb/m}^2 = 1 \frac{\text{N}}{\text{C} \cdot (\text{m/s})} = 1 \frac{\text{N}}{\text{A} \cdot \text{m}}$$

FORCE ON A CURRENT IN A MAGNETIC FIELD: Since a current is simply a stream of positive charges, a current experiences a force due to a magnetic field. The direction of the force is found by the right-hand rule shown in Fig. 30-3, with the direction of the current used in place of the velocity vector.

The magnitude ΔF_M of the force on a small length ΔL of wire carrying current I is given by

$$\Delta F_M = I(\Delta L)B \sin \theta$$

where θ is the angle between the direction of the current I and the direction of the field. For a straight wire of length L in a uniform magnetic field, this becomes

$$F_M = ILB \sin \theta$$

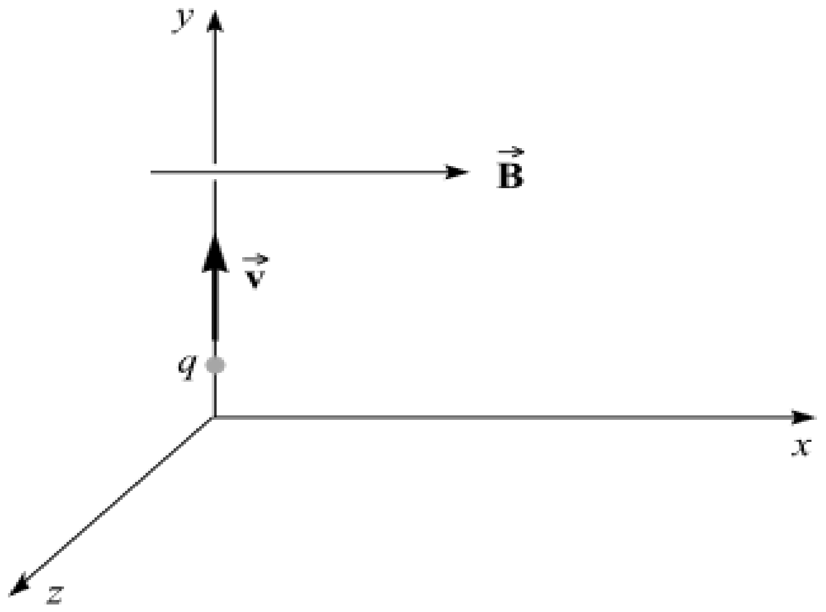
Notice that the force is zero if the wire is in line with the field lines. The force is maximum if the field lines are perpendicular to the wire. In analogy to the case of a moving charge, the force is perpendicular to the plane defined by the wire and the field lines.

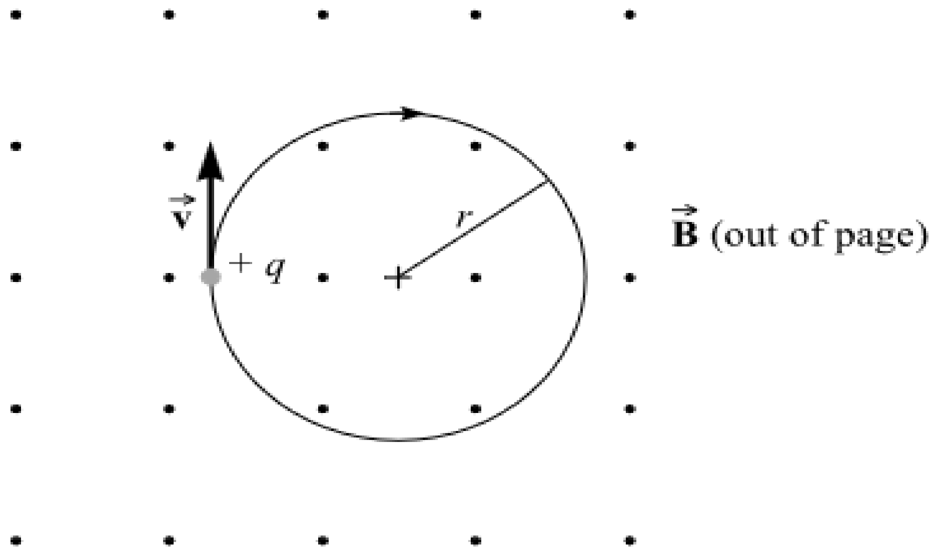
Solved Problems

1\ A uniform magnetic field, $B = 3.0$ G, exists in the $+x$-direction. A proton ($q = +e$) shoots through the field in the $+y$-direction with a speed of 5.0×10^6 m/s. (*a*) Find the magnitude and direction of the force on the proton. (*b*) Repeat with the proton replaced by an electron.

(*a*) The situation is shown in Fig. 30-4. We have, after changing 3.0 G to 3.0×10^{-4} T,

$$F_M = qvB \sin\theta = (1.6 \times 10^{-19}\ \text{C})(5.0 \times 10^6\ \text{m/s})(3.0 \times 10^{-4}\ \text{T}) \sin 90^\circ = 2.4 \times 10^{-16}\ \text{N}$$





2\ A proton enters a magnetic field of flux density 1.5 Wb/m^2 with a velocity of 2.0×10^7 m/s at an angle of 30° with the field. Compute the force on the proton.

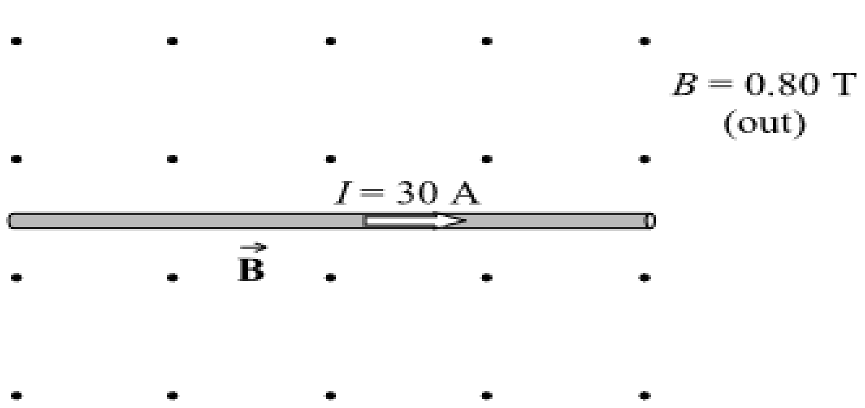
$$F_M = qvB \sin\theta = (1.6 \times 10^{-19}\ \mathrm{C})(2.0 \times 10^7\ \mathrm{m/s})(1.5\ \mathrm{Wb/m^2}) \sin 30° = 2.4 \times 10^{-12}\ \mathrm{N}$$

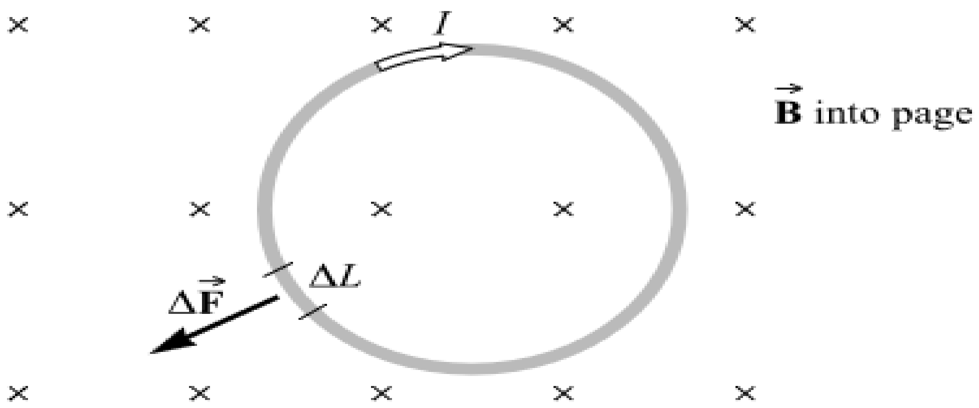
3\ In Fig. 30-8, the magnetic field is out of the page and $B = 0.80$ T. The wire shown carries a current of 30 A. Find the magnitude and direction of the force on a 5.0 cm length of the wire.

We know that

$$\Delta F_M = I(\Delta L)B \sin\theta = (30\ \mathrm{A})(0.050\ \mathrm{m})(0.80\ \mathrm{T})(1) = 1.2\ \mathrm{N}$$

By the right-hand rule, the force is perpendicular to both the wire and the field and is directed toward the bottom of the page.





4\ A flat circular coil with 40 loops of wire has a diameter of 32 cm. What current must flow in its wires to produce a field of 3.0×10^{-4} Wb/m^2 at its center?

From Fig. 31-1(*b*),

$$B = \frac{\mu_0 N I}{2r} \qquad \text{or} \qquad 3.0 \times 10^{-4}\ \text{T} = \frac{(4\pi \times 10^{-7}\ \text{T}\cdot\text{m/A})(40)(I)}{2(0.16\ \text{m})}$$

which gives $I = 1.9$ A.

5\ An air-core solenoid with 2000 loops is 60 cm long and has a diameter of 2.0 cm. If a current of 5.0 A is sent through it, what will be the flux density within it?

From Fig. 31-3(*c*),

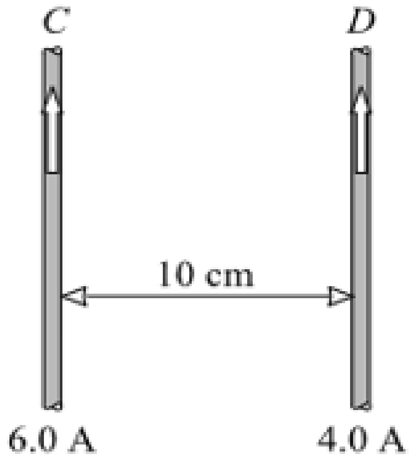
$$B = \mu_0 n I = (4\pi \times 10^{-7}\ \text{T}\cdot\text{m/A})\left(\frac{2000}{0.60\ \text{m}}\right)(5.0\ \text{A}) = 0.021\ \text{T}$$

6\ Compute the value of B in air at a point 5 cm from a long straight wire carrying a current of 15 A.

From Fig. 31-1(a),

$$B = \frac{\mu_0 I}{2\pi r} = \frac{(4\pi \times 10^{-7}\ \mathrm{T\cdot m/A})(15\ \mathrm{A})}{2\pi(0.05\ \mathrm{m})} = 6 \times 10^{-5}\ \mathrm{T}$$

7\ As shown in Fig. 31-5, two long parallel wires are 10 cm apart and carry currents of 6.0 A and 4.0 A. Find the force on a 1.0 m length of wire D if the currents are (a) parallel and (b) anti-parallel.



(*a*) This is the situation shown in Fig. 31-5. The field at wire *D* due to wire *C* is directed into the page and has the value

$$B = \frac{\mu_0 I}{2\pi r} = \frac{(4\pi \times 10^{-7}\ \mathrm{T\cdot m/A})(6.0\ \mathrm{A})}{2\pi(0.10\ \mathrm{m})} = 1.2 \times 10^{-5}\ \mathrm{T}$$

The force on 1 m of wire *D* due to this field is

$$F_M = ILB \sin\theta = (4.0\ \mathrm{A})(1.0\ \mathrm{m})(1.2 \times 10^{-5}\ \mathrm{T})(\sin 90^\circ) = 48\ \mu\mathrm{N}$$

The right-hand rule applied to wire *D* tells us the force on *D* is toward the left. The wires attract each other.

(*b*) If the current in *D* flows in the reverse direction, the force direction will be reversed. The wires will repel each other. The force per meter of length is still 48 μN.

Supplementary Problems

Compute the flux density in air at a point 6.0 cm from a long straight wire carrying a current of 9.0 A. *Ans.* 30 μT

A closely wound, flat, circular coil of 25 turns of wire has a diameter of 10 cm and carries a current of 4.0 A. Determine the value of B at its center. *Ans.* 1.3×10^{-3} Wb/m^2

An air-core solenoid 50 cm long has 4000 loops wound on it. Compute B in its interior when a current of 0.25 A exists in the winding. *Ans.* 2.5 mT

A uniformly wound air-core toroid has 750 loops on it. The radius of the circle through the center of its windings is 5 cm. What current in the winding will produce a field of 1.8 mT on this central circle? *Ans.* 0.6 A

Two long parallel wires are 4 cm apart and carry currents of 2 A and 6 A in the same direction. Compute the force between the wires per meter of wire length. *Ans.* 6×10^{-5} N/m, attraction

An ion $(q = +2e)$ enters a magnetic field of 1.2 Wb/m^2 at a velocity of 2.5×10^5 m/s perpendicular to the field. Determine the force on the ion. *Ans.* 9.6×10^{-14} N

Calculate the speed of ions that pass undeflected through crossed E and B fields for which $E = 7.7$ kV/m and $B = 0.14$ T. *Ans.* 55 km/s

A straight wire 15 cm long, carrying a current of 6.0 A, is in a uniform field of 0.40 T. What is the force on the wire when it is (*a*) at right angles to the field and (*b*) at 30° to the field? *Ans.* (*a*) 0.36 N; (*b*) 0.18 N