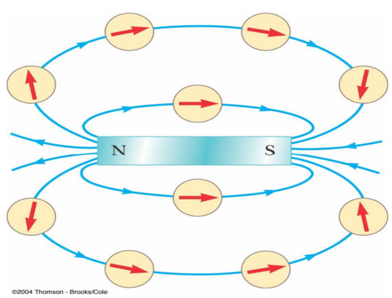
Chapter 29

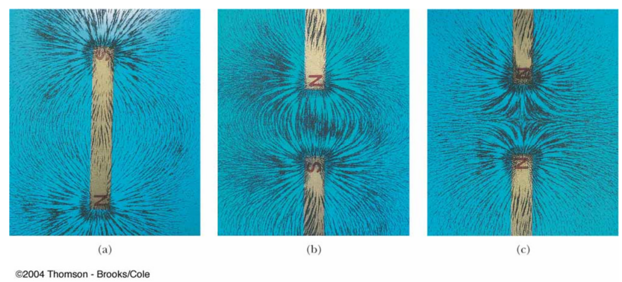
Magnetic fields

29.1 Magnetic fields and forces

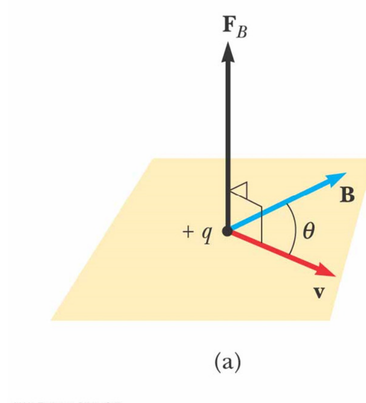
The direction of the magnetic field B at any location is the direction in which a compass needle points at that location.

The magnetic field lines outside the magnet point away from north poles and toward south poles as shown in the figure below.





We can define a magnetic field B at some point in space in terms of the magnetic force F_B *that the field exerts on a test object, for which we use a charged particle* moving with a velocity v.



Assuming that no electric (E) or gravitational (g) fields are present at the location of the test object.

The magnitude F_B *of the magnetic force exerted on the particle is proportional* to the charge *q and to the speed v of the particle.*

The magnitude and direction of F_B *depend on the velocity of the particle V and* on the magnitude and direction of the magnetic field B.

• When a charged particle moves parallel to the magnetic field vector (i.e., $\theta = 0$) , the magnetic force acting on the particle is zero.

• When the particle's velocity vector makes any angle with the magnetic field, the magnetic force acts in a direction perpendicular to both v and B; F_B *is perpendicular to the plane formed by v and B*

• The magnetic force exerted on a positive charge is in the direction opposite the direction of the magnetic force exerted on a negative charge moving in the same direction.

• The magnitude of the magnetic force exerted on the moving particle is proportional to sinθ , where is the angle the particle’s velocity vector makes with the direction of B.

We can summarize these observations by writing the magnetic force in the form

$$\vec{F}_B = q\ \vec{\mathrm{v}}\mathrm{x}\vec{\mathrm{B}} = \mathrm{q}|\vec{\mathrm{v}}||\vec{\mathrm{B}}|\ \sin\theta \qquad 29.1$$

From Equation 29.2, we see that the SI unit of magnetic field is the newton per coulomb-meter per second, which is called the **tesla** (T):

$$1\ \mathrm{T} = \frac{\mathrm{N}}{\mathrm{C}\cdot\mathrm{m/s}}$$

Because a coulomb per second is defined to be an ampere, we see that

$$1\ \mathrm{T} = 1\ \frac{\mathrm{N}}{\mathrm{A}\cdot\mathrm{m}}$$

when a charged particle moves with a velocity **v** through a magnetic field, the field can alter the direction of the velocity vector but cannot change the speed or kinetic energy of the particle.

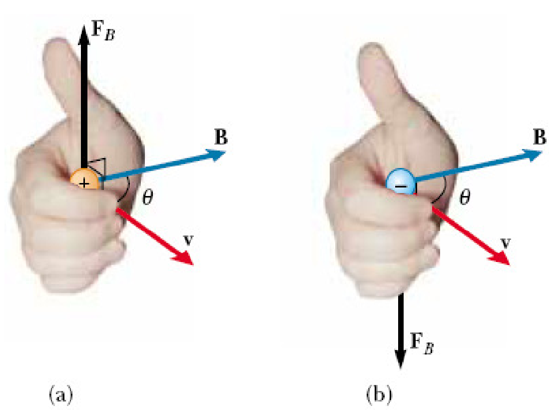
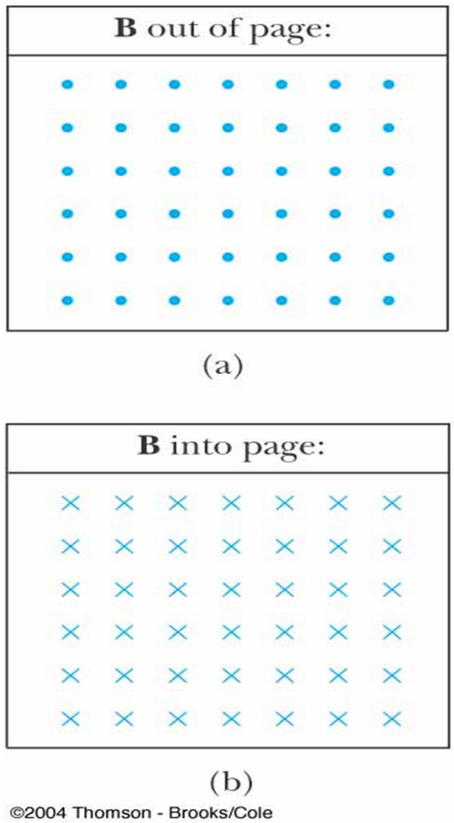


Figure 29.4 The right-hand rule for determining the direction of the magnetic force $\mathbf{F}_B = q\mathbf{v} \times \mathbf{B}$ acting on a particle with charge q moving with a velocity **v** in a magnetic field **B**. The direction of $\mathbf{v} \times \mathbf{B}$ is the direction in which the thumb points. (a) If q is positive, $\mathbf{F}_B$ is upward. (b) If q is negative, $\mathbf{F}_B$ is downward, antiparallel to the direction in which the thumb points.



Examples:

Magnetic field

Example 1:

An electron in a television picture tube moves toward the front of the tube with a speed of 8.0×10^6 m/s along the *x* axis. Surrounding the neck of the tube are coils of wire that create a magnetic field of magnitude 0.025 T, directed at an angle of 60° to the *x axis and lying in the xy* plane. Calculate the magnetic force on and acceleration of the electron.

Example 29.1 An Electron Moving in a Magnetic Field

An electron in a television picture tube moves toward the front of the tube with a speed of 8.0×10^6 m/s along the x axis (Fig. 29.5). Surrounding the neck of the tube are coils of wire that create a magnetic field of magnitude 0.025 T, directed at an angle of 60° to the x axis and lying in the xy plane.

(A) Calculate the magnetic force on the electron using Equation 29.2.

Solution Using Equation 29.2, we find the magnitude of the magnetic force:

$$\begin{aligned} F_B &= |q|vB \sin\theta \\ &= (1.6 \times 10^{-19}\ \text{C})(8.0 \times 10^6\ \text{m/s})(0.025\ \text{T})(\sin 60°) \\ &= \boxed{2.8 \times 10^{-14}\ \text{N}} \end{aligned}$$

Because $\mathbf{v} \times \mathbf{B}$ is in the positive z direction (from the right-hand rule) and the charge is negative, $\mathbf{F}_B$ is in the negative z direction.

(B) Find a vector expression for the magnetic force on the electron using Equation 29.1.

Solution We begin by writing a vector expression for the velocity of the electron:

$$\mathbf{v} = (8.0 \times 10^6\ \hat{\mathbf{i}})\ \text{m/s}$$

and one for the magnetic field:

$$\begin{aligned} \mathbf{B} &= (0.025 \cos 60° \hat{\mathbf{i}} + 0.025 \sin 60° \hat{\mathbf{j}})\text{T} \\ &= (0.013\,\hat{\mathbf{i}} + 0.022\,\hat{\mathbf{j}})\text{T} \end{aligned}$$

The force on the electron, using Equation 29.1, is

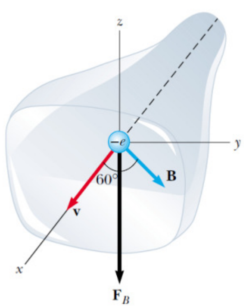


Figure 29.5 (Example 29.1) The magnetic force $\mathbf{F}_B$ acting on the electron is in the negative z direction when $\mathbf{v}$ and $\mathbf{B}$ lie in the xy plane.

$$\begin{aligned} \mathbf{F}_B &= q\mathbf{v} \times \mathbf{B} \\ &= (-e)[(8.0 \times 10^6\,\hat{\mathbf{i}})\ \text{m/s}] \times [(0.013\,\hat{\mathbf{i}} + 0.022\,\hat{\mathbf{j}})\text{T}] \\ &= (-e)[(8.0 \times 10^6\,\hat{\mathbf{i}})\ \text{m/s}] \times [(0.013\,\hat{\mathbf{i}})\text{T}] \\ &\quad + (-e)[(8.0 \times 10^6\,\hat{\mathbf{i}})\ \text{m/s}] \times [(0.022\,\hat{\mathbf{j}})\text{T}] \\ &= (-e)(8.0 \times 10^6\ \text{m/s})(0.013\ \text{T})(\hat{\mathbf{i}} \times \hat{\mathbf{i}}) \\ &\quad + (-e)(8.0 \times 10^6\ \text{m/s})(0.022\ \text{T})(\hat{\mathbf{i}} \times \hat{\mathbf{j}}) \\ &= (-1.6 \times 10^{-19}\ \text{C})(8.0 \times 10^6\ \text{m/s})(0.022\ \text{T})\,\hat{\mathbf{k}} \end{aligned}$$

where we have used Equations 11.7a and 11.7b to evaluate $\hat{\mathbf{i}} \times \hat{\mathbf{i}}$ and $\hat{\mathbf{i}} \times \hat{\mathbf{j}}$. Carrying out the multiplication, we find,

$$\mathbf{F}_B = \boxed{(-2.8 \times 10^{-14}\ \text{N})\hat{\mathbf{k}}}$$

This expression agrees with the result in part (A). The magnitude is the same as we found there, and the force vector is in the negative z direction.

Example2:

An electron moving along the positive *x axis perpendicular* to a magnetic field experiences a magnetic deflection in the negative *y direction. What is the direction of* the magnetic field?

Example 3:

A proton moves in a direction perpendicular to a uniform magnetic field B at 1.0 x10^7 m/s and experiences an acceleration of 2.0x10^{13} m/s^2 in the + x direction when its velocity is in the +z direction. Determine the magnitude and direction of the field.