

Answer to Essential Question 19.6: In this situation, the forces acting on the two short sides of the loop produce forces that cancel one another. These forces are either zero or are directed along the axis we take torques around, giving no torque about that axis.

19-7 Magnetic Field from a Long Straight Wire

Let's now turn to investigating how to produce a magnetic field. Similar to the way that electric fields can be set up by charged particles and act on charged particles, magnetic fields can be set up by moving charges (or currents) and act on moving charges. The analog of the point charge for magnetism is the long straight current-carrying wire. Figure 19.23 shows the magnetic field from a long straight wire. The magnetic field from a wire decreases with distance from the wire. Instead of the field being proportional to the inverse square of the distance, as is the electric field from a point charge, the magnetic field is inversely proportional to the distance from the wire. Another difference between the electric field situation and the magnetic field situation is that the magnetic field lines are complete loops.

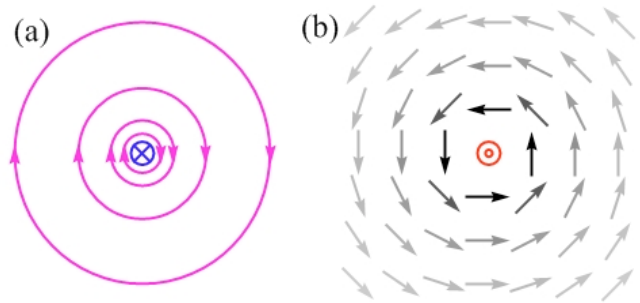


Figure 19.23: The magnetic field lines from a long straight wire wrap around the wire in circular loops. In (a), we see magnetic field lines near a wire that carries current into the page. In (b), field vectors are plotted. The vectors circulate counterclockwise, because the current in (b) is out of the page, opposite to what it is in (a). Both views show the strength of the magnetic field decreasing as the distance from the wire increases.

The magnetic field at a distance r from a long straight wire carrying a current I is:

$$B = \frac{\mu_0 I}{2\pi r}. \quad (\text{Eq. 19.9: The magnetic field from a long-straight wire})$$

The direction of the magnetic field is given by a right-hand rule. In this rule, point the thumb on your right hand in the direction of the current in the wire. When you curl your fingers, they curl the same way that the magnetic field curls around the wire. The constant μ_0 in equation 19.9 is known as the **permeability of free space**, and has a value of $\mu_0 = 4\pi \times 10^{-7} \text{ T m / A}$.

In Chapter 8, we analyzed situations involving objects with mass interacting with each other via the force of gravity. In Chapter 16, we investigated situations involving interacting charged particles. Let's investigate analogous magnetic situations involving long straight wires.

EXPLORATION 19.7 – The magnetic force between two parallel wires

A long straight wire (wire 1) carries a current of I_1 into the page. A second long straight wire (wire 2) is located a distance d to the right of wire 1, and carries a current of I_2 into the page. Let's determine the force per unit length experienced by wire 2 because of wire 1.

Step 1 – Find the magnitude and direction of the magnetic field set up by wire 1 at the location of wire 2. The magnitude of the field is given by equation 19.9: $B_1 = \mu_0 I_1 / (2\pi d)$. To find the direction of this field at the location of wire 2, recall that the field lines are circular loops centered on wire 1. Applying the right-hand rule (see the previous page), we find that these field lines go clockwise. The field at any point is tangent to the field line, so the field at the location of wire 2 is directed straight down (see Figure 19.24).

Step 2 – Apply equation 19.7 to find the force per unit length that wire 2 experiences because of the magnetic field of wire 1.

Equation 19.7 ($F_M = ILB \sin\theta$) gives us the

force a wire of length L experiences in a magnetic field. However, we do not have a length to use for wire 2, so we bring the factor of length to the left side. Substituting the expression for B_1 from step 1 gives:

$$\frac{F_{12}}{L} = I_2 B_1 \sin(90^\circ) = \frac{\mu_0 I_1 I_2}{2\pi d} \quad (\text{Eq. 19.10: The force between two parallel wires})$$

Applying the right-hand rule associated with equation 19.7, we find that the force experienced by wire 2 is to the left. In other words, when the currents are in the same direction the wires attract. If the currents are in opposite directions, they repel.

Step 3 – Which wire exerts more force on the other, if $I_1 = 3I_2$? No matter how the currents compare, the wires experience forces of equal magnitude in opposite directions – Newton’s third law applies. Another way to see this is that equation 19.10 applies equally well to either wire.

Key ideas: Two long straight wires that are parallel to one another exert forces on one another. If the currents are in the same direction, the wires attract one another. If the currents are in the opposite direction, the wires repel one another. **Related End-of-Chapter Exercises: 49 and 57.**

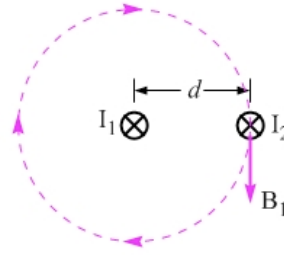


Figure 19.24: The magnetic field set up by wire 1 at the location of wire 2 is directed down the page, tangent to the direction of wire 1’s field line at that point.

EXAMPLE 19.7 – Finding the net magnetic field

Four long straight parallel wires pass through the x - y plane at a distance of 4.0 cm from the origin. Figure 19.25 shows the location of each wire, and its current. Find the net magnetic field at the origin because of these wires.

SOLUTION

Let’s apply the principle of superposition to find the net magnetic field at the origin. The four fields, one from each wire, are shown in Figure 19.26. The two fields that are along the y -axis, from the two wires on the x -axis, cancel one another. The two fields along the x -axis, from the wires on the y -axis, add together. Thus, the net magnetic field at the origin is directed along the positive x -axis, and has a magnitude of:

$$B_{net} = B_1 + B_3 = \frac{\mu_0 I_1}{2\pi r} + \frac{\mu_0 I_3}{2\pi r} = \frac{\mu_0}{2\pi r} (I_1 + I_3) = \frac{4\pi \times 10^{-7} \text{ T m/A}}{2\pi (0.040 \text{ m})} (30 \text{ A} + 10 \text{ A}) = 2.0 \times 10^{-4} \text{ T} .$$

Note that magnetic field is a vector. We can add the magnitudes of the two individual fields to find the magnitude of the net field only because the two fields are in the same direction.

Related End-of-Chapter Exercises: 11, 24 – 27.

Essential Question 19.7: For the situation in Exploration 19.7, let’s say that the two wires are 40 cm apart and that $I_1 = 3I_2$. Where is the net magnetic field equal to zero near these wires?

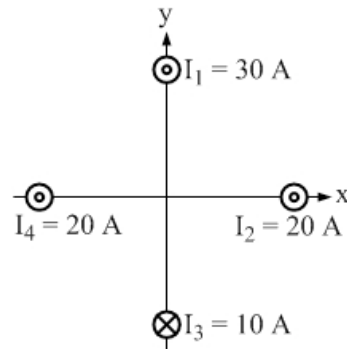


Figure 19.25: The currents carried by four long straight wires.

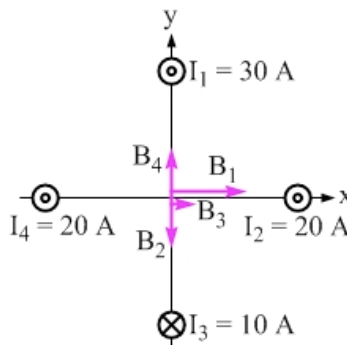


Figure 19.26: The four fields that add as vectors to give the net field.