7.9: The Biot-Savart Law

Learning Objectives

By the end of this section, you will be able to:

- Explain how to derive a magnetic field from an arbitrary current in a line segment
- Calculate magnetic field from the Biot-Savart law in specific geometries, such as a current in a line and a current in a circular arc
- Explain how the Biot-Savart law is used to determine the magnetic field due to a thin, straight wire.
- Determine the dependence of the magnetic field from a thin, straight wire based on the distance from it and the current flowing in the wire.
- Sketch the magnetic field created from a thin, straight wire by using the second right-hand rule.
- Explain how parallel wires carrying currents can attract or repel each other
- Define the ampere and describe how it is related to current-carrying wires
- Calculate the force of attraction or repulsion between two current-carrying wires

We have seen that mass produces a gravitational field and also interacts with that field. Charge produces an electric field and also interacts with that field. Since moving charge (that is, current) interacts with a magnetic field, we might expect that it also creates that field—and it does.

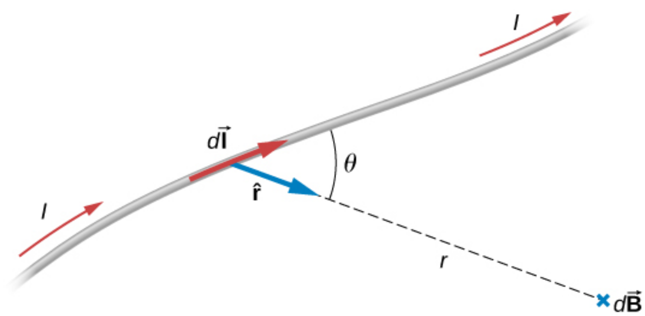


Figure 7.9.1: A current element $Id\vec{l}$ produces a magnetic field at point P given by the Biot-Savart law (Equation 7.9.4).

The equation used to calculate the magnetic field produced by a current is known as the Biot-Savart law. It is an empirical law named in honor of two scientists who investigated the interaction between a straight, current-carrying wire and a permanent magnet. This law enables us to calculate the magnitude and direction of the magnetic field produced by a current in a wire. The **Biot-Savart law** states that at any point P (Figure 7.9.1), the magnetic field $d\vec{B}$ due to an element $d\vec{l}$ of a current-carrying wire is given by

$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{Id\vec{l}\times\hat{r}}{r^2}. \tag{7.9.1}$$

The constant μ_0 is known as the **permeability of free space** and is exactly

$$\mu_0 = 4\pi\times10^{-7}\,T\cdot m/A \tag{7.9.2}$$

in the SI system. The infinitesimal wire segment $d\vec{l}$ is in the same direction as the current I (assumed positive), r is the distance from $d\vec{l}$ to P and $\hat{r}$ is a unit vector that points from $d\vec{l}$ to P, as shown in Figure 7.9.1. The direction of $d\vec{B}$ is determined by applying the right-hand rule to the vector product $d\vec{l}\times\hat{r}$. The magnitude of $d\vec{B}$ is

$$dB = \frac{\mu_0}{4\pi}\frac{I\,dl\,\sin\theta}{r^2} \tag{7.9.3}$$

where θ is the angle between $d\vec{l}$ and $\hat{r}$. Notice that if $\theta = 0$, then $d\vec{B} = \vec{0}$. The field produced by a current element $Id\vec{l}$ has no component parallel to $d\vec{l}$.

The magnetic field due to a finite length of current-carrying wire is found by integrating Equation 7.9.2 along the wire, giving us the usual form of the Biot-Savart law.

Biot-Savart law

The magnetic field $\vec{B}$ due to an element $d\vec{l}$ of a current-carrying wire is given by

$$\vec{B} = \frac{\mu_0}{4\pi}\int_{wire}\frac{I\,d\vec{l}\times\hat{r}}{r^2}. \tag{7.9.4}$$

Since this is a vector integral, contributions from different current elements may not point in the same direction. Consequently, the integral is often difficult to evaluate, even for fairly simple geometries. The following strategy may be helpful.

Problem-Solving Strategy: Solving Biot-Savart Problems

To solve Biot-Savart law problems, the following steps are helpful:

1. Identify that the Biot-Savart law is the chosen method to solve the given problem. If there is symmetry in the problem comparing $\vec{B}$ and $d\vec{l}$, Ampère's law may be the preferred method to solve the question.
2. Draw the current element length $d\vec{l}$ and the unit vector $\hat{r}$ noting that $d\vec{l}$ points in the direction of the current and $\hat{r}$ points from the current element toward the point where the field is desired.
3. Calculate the cross product $d\vec{l}\times\hat{r}$ .The resultant vector gives the direction of the magnetic field according to the Biot-Savart law.
4. Use Equation 7.9.4 and substitute all given quantities into the expression to solve for the magnetic field. Note all variables that remain constant over the entire length of the wire may be factored out of the integration.
5. Use the right-hand rule to verify the direction of the magnetic field produced from the current or to write down the direction of the magnetic field if only the magnitude was solved for in the previous part.

Example 7.9.1: Calculating Magnetic Fields of Short Current Segments

A short wire of length 1.0 cm carries a current of 2.0 A in the vertical direction (Figure 7.9.2). The rest of the wire is shielded so it does not add to the magnetic field produced by the wire. Calculate the magnetic field at point **P**, which is 1 meter from the wire in the **x**-direction.

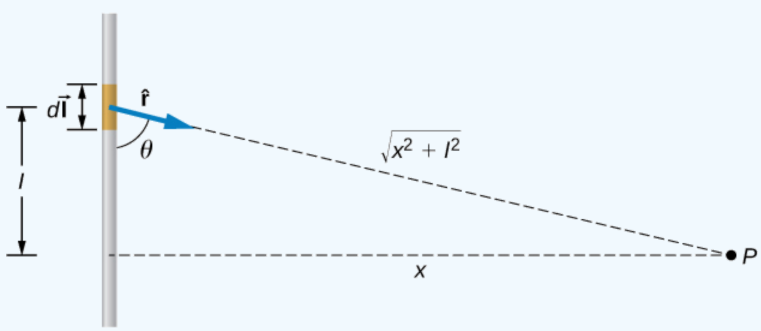


Figure 7.9.2: A small line segment carries a current I in the vertical direction. What is the magnetic field at a distance **x** from the segment?

Strategy

We can determine the magnetic field at point P using the Biot-Savart law. Since the current segment is much smaller than the distance **x**, we can drop the integral from the expression. The integration is converted back into a summation, but only for small dl, which we now write as Δl. Another way to think about it is that each of the radius values is nearly the same, no matter where the current element is on the line segment, if Δl is small compared to **x**. The angle θ is calculated using a tangent function. Using the numbers given, we can calculate the magnetic field at P.

Solution

The angle between $\Delta\vec{l}$ and $\hat{r}$ is calculated from trigonometry, knowing the distances **l** and **x** from the problem:

$$\theta = \tan^{-1}\left(\frac{1\,m}{0.01\,m}\right) = 89.4^o.$$

The magnetic field at point P is calculated by the Biot-Savart law (Equation 7.9.3):

$$\begin{aligned} B &= \frac{\mu_0}{4\pi}\frac{I\Delta l\,\sin\theta}{r^2} \\ &= (1\times 10^{-7} T\cdot m/A)\left(\frac{2\,A(0.01\,m)\,sin\,(89.4^o)}{(1\,m)^2}\right) \\ &= 2.0\times 10^{-9} T. \end{aligned}$$

From the right-hand rule and the Biot-Savart law, the field is directed into the page.

Significance

This approximation is only good if the length of the line segment is very small compared to the distance from the current element to the point. If not, the integral form of the Biot-Savart law must be used over the entire line segment to calculate the magnetic field.

? Exercise 7.9.1

Using Example 7.9.1, at what distance would **P** have to be to measure a magnetic field half of the given answer?

Solution

1.41 meters

Example 7.9.2: Calculating Magnetic Field of a Circular Arc of Wire

A wire carries a current **I** in a circular arc with radius **R** swept through an arbitrary angle θ (Figure 7.9.3). Calculate the magnetic field at the center of this arc at point **P**.

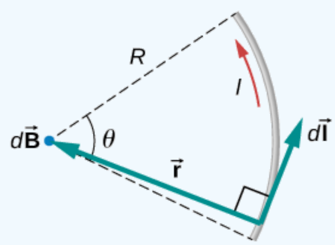


Figure 7.9.3: A wire segment carrying a current **I**. The path $d\vec{l}$ and radial direction $\hat{r}$ are indicated.

Strategy

We can determine the magnetic field at point **P** using the Biot-Savart law. The radial and path length directions are always at a right angle, so the cross product turns into multiplication. We also know that the distance along the path **dl** is related to the radius times the angle θ (in radians). Then we can pull all constants out of the integration and solve for the magnetic field.

Solution

The Biot-Savart law starts with the following equation:

$$\vec{B} = \frac{\mu_0}{4\pi}\int_{wire}\frac{I d\vec{l}\times\hat{r}}{r^2}.$$

As we integrate along the arc, all the contributions to the magnetic field are in the same direction (out of the page), so we can work with the magnitude of the field. The cross product turns into multiplication because the path dl and the radial direction are perpendicular. We can also substitute the arc length formula, $dl = r\,d\theta$:

$$B = \frac{\mu_0}{4\pi}\int_{wire}\frac{I r\,d\theta}{r^2}.$$

The current and radius can be pulled out of the integral because they are the same regardless of where we are on the path. This leaves only the integral over the angle,

$$B = \frac{\mu_0 I}{4\pi r} \int_{wire} d\theta.$$

The angle varies on the wire from 0 to θ; hence, the result is

$$B = \frac{\mu_0 I\theta}{4\pi r}.$$

Significance

The direction of the magnetic field at point P is determined by the right-hand rule, as shown in the previous chapter. If there are other wires in the diagram along with the arc, and you are asked to find the net magnetic field, find each contribution from a wire or arc and add the results by superposition of vectors. Make sure to pay attention to the direction of each contribution. Also note that in a symmetric situation, like a straight or circular wire, contributions from opposite sides of point P cancel each other.

Exercise 7.9.2

The wire loop forms a full circle of radius **R** and current **I**. What is the magnitude of the magnetic field at the center?

Solution

$\frac{\mu_0 I}{2R}$

Magnetic Field of a Long Straight Wire

We begin by computing the field of a long-straight wire that carries a current I. Aside from the vectors, the procedure follows almost exactly the same path as the case of the electric field of a long line of charge.

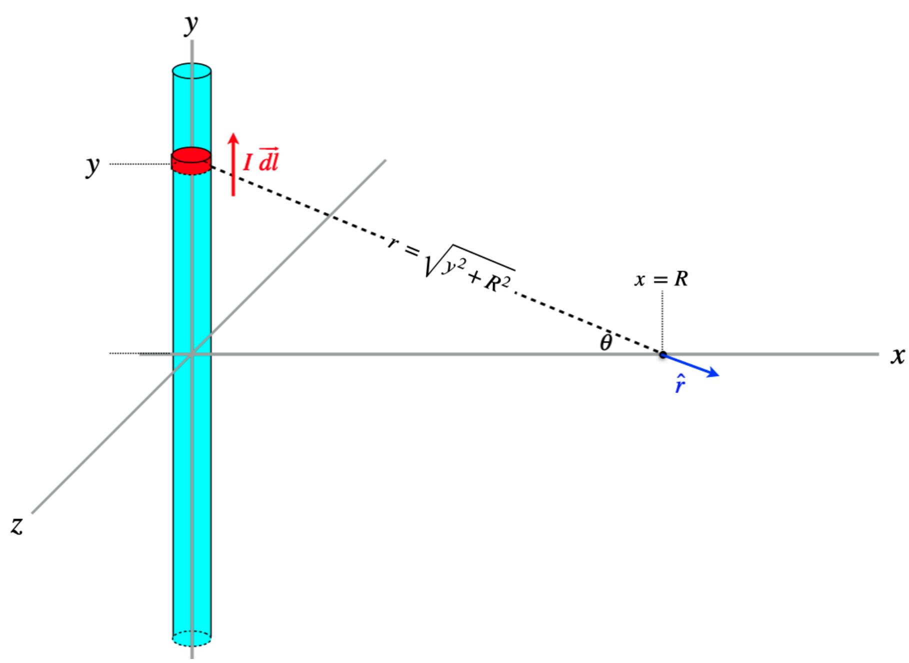


Figure 7.9.4: **– Calculating Magnetic Field of Long, Straight Wire**

One of the key differences between computing magnetic fields and electric fields is that while we were able to use symmetry to help us solve for components of the electric field, in the case of the magnetic field, this is much harder to do, and is much safer to just get all the vectors right and trust vector math thereafter. We could have used this "trust the vector math" approach for the electric field as well, of course, but the necessity of using it in cases where cross-products are involved becomes quickly apparent.

Okay, we start by expressing all the relevant quantities in terms of our chosen coordinate system:

$$\vec{dl} = dy\;\hat{j} \qquad \hat{r} = \cos\theta\;\hat{i} - \sin\theta\;\hat{j} \qquad \cos\theta = \frac{R}{\sqrt{y^2+R^2}} \tag{7.9.5}$$

Next, write down Biot-Savart's law for the current element, and simplify:

$$\begin{aligned} d\vec{B} &= \left(\frac{\mu_o}{4\pi}\right)\frac{I}{R^2}\vec{dl}\times\hat{r} \\ &= \left(\frac{\mu_o I}{4\pi}\right)\frac{dy}{y^2+R^2}\hat{j}\times\left(\cos\theta\;\hat{i}-\sin\theta\;\hat{j}\right) \\ &= \left(\frac{\mu_o I}{4\pi}\right)\frac{dy}{y^2+R^2}\left(\cos\theta\;\;\cancelto{-\hat{k}}{\hat{j}\times\hat{i}} - \sin\theta\;\;\cancelto{-0}{\hat{j}\times\hat{j}}\right) \\ &= \left(\frac{\mu_o I}{4\pi}\right)\frac{dy}{y^2+R^2}\left(\frac{R}{\sqrt{y^2+R^2}}\right)\left(-\hat{k}\right) \\ &= \left(\frac{\mu_o I\;R}{4\pi}\right)\frac{dy}{\left(y^2+R^2\right)^{\frac{3}{2}}}\left(-\hat{k}\right) \end{aligned} \tag{7.9.6}$$

All that remains is to add up the contributions to the field from all the current elements, which means integrating this from $y=-\infty$ to $y=+\infty$:

$$\begin{aligned} \vec{B} &= \left(-\hat{k}\right)\left(\frac{\mu_o I\;R}{4\pi}\right)\int\limits_{-\infty}^{+\infty}\frac{dy}{\left(y^2+R^2\right)^{\frac{3}{2}}} \\ &= \left(-\hat{k}\right)\left(\frac{\mu_o I\;R}{4\pi}\right)\left[\frac{1}{R^2}\;\frac{y}{\sqrt{y^2+R^2}}\right]_{-\infty}^{+\infty} \\ &= \left(-\hat{k}\right)\left(\frac{\mu_o I}{4\pi R}\right)[2] \\ &= \left(\frac{\mu_o I}{2\pi R}\right)\left(-\hat{k}\right) \end{aligned} \tag{7.9.7}$$

The resemblance the magnitude of this field bears to that of the electric field (Equation 1.5.2) is interesting, though not all that surprising, given that both fields weaken with distance from the source according to an inverse-square law. The direction of the magnetic field vector is tangent to a circle centered at the line of the current, and circles around the current line.

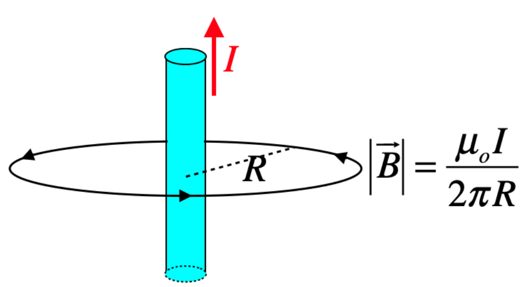


Figure 7.9.5: **– Magnetic Field Circulates Around the Long, Straight Wire**

As with the electric field, the magnetic field obeys superposition, which means we can combine the result of this physical situation with others to get a net magnetic field. It is also worth noting that both the moving point charge and the long, straight wire yield magnetic fields whose line close back on themselves (form closed loops) – in nether case does a field emanate out of or into the source. There are no magnetic monopole fields.

Magnetic Field of a Long Straight Wire

How much current is needed to produce a significant magnetic field, perhaps as strong as Earth's field? Surveyors will tell you that overhead electric power lines create magnetic fields that interfere with their compass readings. Indeed, when Oersted discovered in 1820 that a current in a wire affected a compass needle, he was not dealing with extremely large currents. How does the shape of wires carrying current affect the shape of the magnetic field created? We noted in Chapter 28 that a current loop created a magnetic field similar to that of a bar magnet, but what about a straight wire? We can use the Biot-Savart law to answer all of these questions, including determining the magnetic field of a long straight wire.

Figure $7.9.1$ shows a section of an infinitely long, straight wire that carries a current **I**. What is the magnetic field at a point **P**, located a distance **R** from the wire?

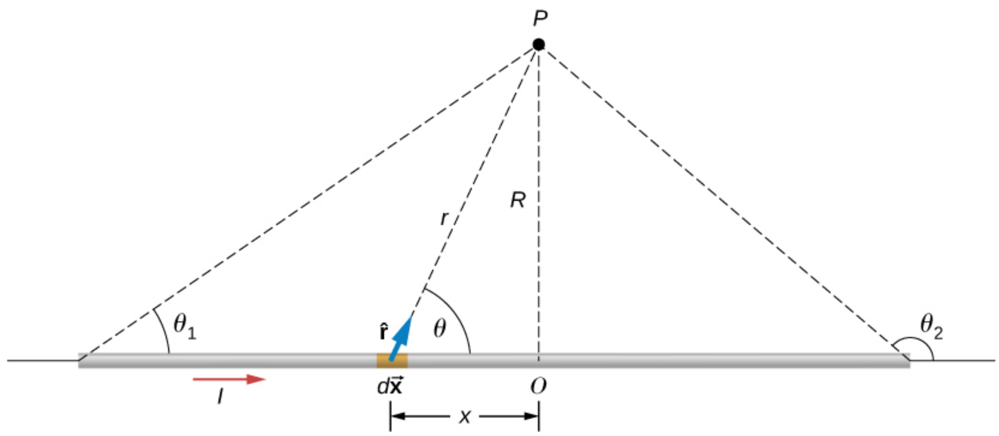


Figure 7.9.6: A section of a thin, straight current-carrying wire. The independent variable θ has the limits θ_1 and θ_2.

Let's begin by considering the magnetic field due to the current element $I\,d\vec{x}$ located at the position **x**. Using the right-hand rule 1 from the previous chapter, $d\vec{x} \times \hat{r}$ points out of the page for any element along the wire. At point P, therefore, the magnetic fields due to all current elements have the same direction. This means that we can calculate the net field there by evaluating the scalar sum of the contributions of the elements. With

$$|d\vec{x} \times \hat{r}| = (dx)(1)\,\sin\theta \tag{7.9.8}$$

we have from the **Biot-Savart law**

$$B = \frac{\mu_0}{4\pi}\int_{wire} \frac{I\,\sin\theta\,dx}{r^2}. \tag{7.9.9}$$

The wire is symmetrical about point O, so we can set the limits of the integration from zero to infinity and double the answer, rather than integrate from negative infinity to positive infinity. Based on the picture and trigonometry, we can write expressions for r and $\sin\theta$ in terms of **x** and **R**, namely:

$$r = \sqrt{x^2 + R^2} \tag{7.9.10}$$

$$\sin\theta = \frac{R}{\sqrt{x^2 + R^2}}. \tag{7.9.11}$$

Substituting these expressions into Equation 7.9.9, the magnetic field integration becomes

$$B = \frac{\mu_0 I}{2\pi}\int_0^\infty \frac{R\,dx}{(x^2 + R^2)^{3/2}}. \tag{7.9.12}$$

Evaluating the integral yields

$$B = \frac{\mu_0 I}{2\pi R}\left[\frac{x}{(x^2 + R^2)^{1/2}}\right]_0^\infty. \tag{7.9.13}$$

Substituting the limits gives us the solution

$$\boxed{B = \frac{\mu_0 I}{2\pi R}.} \tag{7.9.14}$$

The magnetic field lines of the infinite wire are circular and centered at the wire (Figure $7.9.2$), and they are identical in every plane perpendicular to the wire. Since the field decreases with distance from the wire, the spacing of the field lines must increase correspondingly with distance. The direction of this magnetic field may be found with a second form of the **right-hand rule** (Figure $7.9.2$). If you hold the wire with your right hand so that your thumb points along the current, then your fingers wrap around the wire in the same sense as $\vec{B}$.

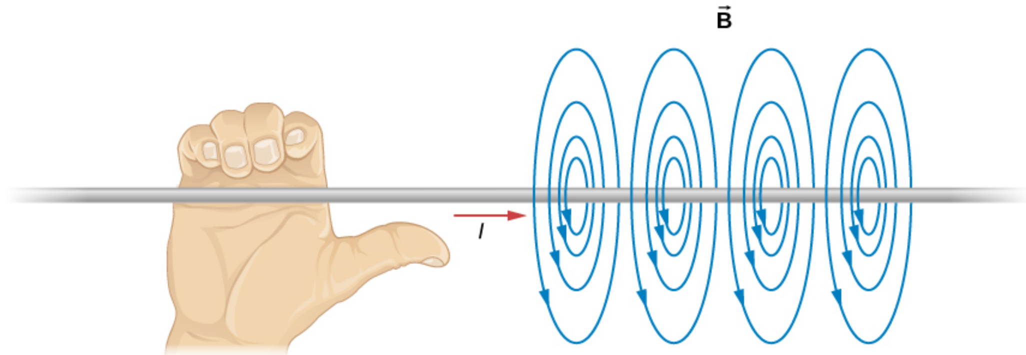


Figure $7.9.7$:. Some magnetic field lines of an infinite wire. The direction of B can be found with a form of the right-hand rule.

The direction of the field lines can be observed experimentally by placing several small compass needles on a circle near the wire, as illustrated in Figure $7.9.3a$. When there is no current in the wire, the needles align with Earth's magnetic field. However, when a large current is sent through the wire, the compass needles all point tangent to the circle. Iron filings sprinkled on a horizontal surface also delineate the field lines, as shown in Figure $7.9.3b$.

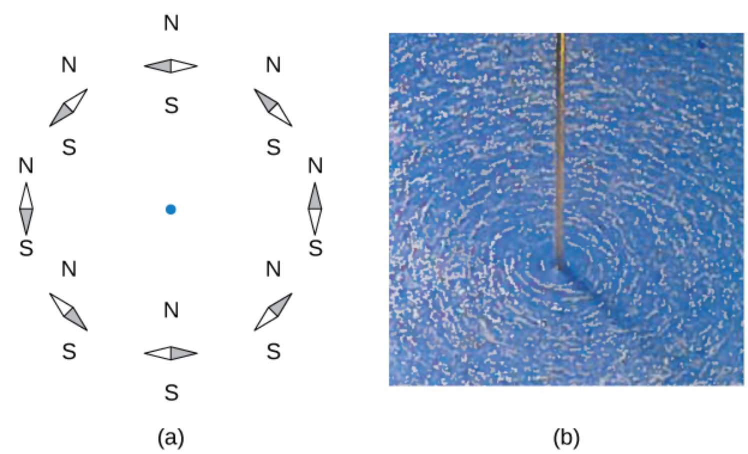


Figure $7.9.3$: The shape of the magnetic field lines of a long wire can be seen using (a) small compass needles and (b) iron filings.

Example $7.9.3$: Calculating Magnetic Field Due to Three Wires

Three wires sit at the corners of a square, all carrying currents of 2 amps into the page as shown in Figure $7.9.4$. Calculate the magnitude of the magnetic field at the other corner of the square, point **P**, if the length of each side of the square is 1 cm.

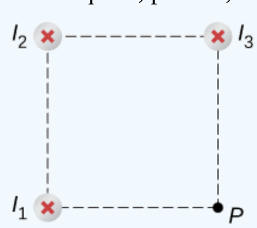


Figure $7.9.8$: Three wires have current flowing into the page. The magnetic field is determined at the fourth corner of the square.

Strategy

The magnetic field due to each wire at the desired point is calculated. The diagonal distance is calculated using the Pythagorean theorem. Next, the direction of each magnetic field's contribution is determined by drawing a circle centered at the point of the wire and out toward the desired point. The direction of the magnetic field contribution from that wire is tangential to the curve. Lastly, working with these vectors, the resultant is calculated.

Solution

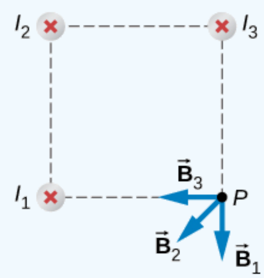
Wires 1 and 3 both have the same magnitude of magnetic field contribution at point **P**:

$$B_1 = B_3 = \frac{\mu_0 I}{2\pi R} = \frac{(4\pi \times 10^{-7} T \cdot m/A)(2\,A)}{2\pi(0.01\,m)} = 4 \times 10^{-5} T. \tag{7.9.15}$$

Wire 2 has a longer distance and a magnetic field contribution at point **P** of:

$$B_2 = \frac{\mu_0 I}{2\pi R} = \frac{(4\pi \times 10^{-7} T \cdot m/A)(2\,A)}{2\pi(0.01414\,m)} = 3 \times 10^{-5} T. \tag{7.9.16}$$

The vectors for each of these magnetic field contributions are shown.



The magnetic field in the **x**-direction has contributions from wire 3 and the **x**-component of wire 2:

$$B_{net\,x} = -4 \times 10^{-5} T - 2.83 \times 10^{-5} T\ \cos(45^o) = -6 \times 10^{-5} T. \tag{7.9.17}$$

The **y**-component is similarly the contributions from wire 1 and the **y**-component of wire 2:

$$B_{net\,y} = -4 \times 10^{-5} T - 2.83 \times 10^{-5} T\ \sin(45^o) = -6 \times 10^{-5} T. \tag{7.9.18}$$

Therefore, the net magnetic field is the resultant of these two components:

$$B_{net} = \sqrt{B^2_{net\,x} + B_{net\,y}} \tag{7.9.19}$$

$$= \sqrt{(-6 \times 10^{-5} T)^2 + (-6 \times 10^{-5} T)^2} \tag{7.9.20}$$

$$= 8.48 \times 10^{-5} T. \tag{7.9.21}$$

Significance

The geometry in this problem results in the magnetic field contributions in the **x**- and **y**-directions having the same magnitude. This is not necessarily the case if the currents were different values or if the wires were located in different positions. Regardless of the numerical results, working on the components of the vectors will yield the resulting magnetic field at the point in need.

? Exercise 7.9.3

Using Example 7.9.1, keeping the currents the same in wires 1 and 3, what should the current be in wire 2 to counteract the magnetic fields from wires 1 and 3 so that there is no net magnetic field at point P?

Solution

4 amps flowing out of the page

Magnetic Force between Two Parallel Currents

You might expect that two current-carrying wires generate significant forces between them, since ordinary currents produce magnetic fields and these fields exert significant forces on ordinary currents. But you might not expect that the force between wires is used to define the ampere. It might also surprise you to learn that this force has something to do with why large circuit breakers burn up when they attempt to interrupt large currents.

The force between two long, straight, and parallel conductors separated by a distance **r** can be found by applying what we have developed in the preceding sections. Figure 7.9.1 shows the wires, their currents, the field created by one wire, and the consequent force the other wire experiences from the created field. Let us consider the field produced by wire 1 and the force it exerts on wire 2 (call the force F_2). The field due to I_1 at a distance **r** is

$$B_1 = \frac{\mu_0 I_1}{2\pi r} \tag{7.9.22}$$

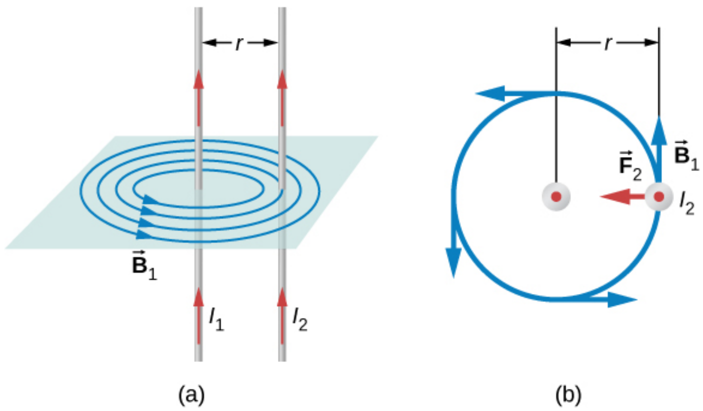


Figure 7.9.9: (a) The magnetic field produced by a long straight conductor is perpendicular to a parallel conductor, as indicated by right-hand rule (RHR)-2. (b) A view from above of the two wires shown in (a), with one magnetic field line shown for wire 1. RHR-1 shows that the force between the parallel conductors is attractive when the currents are in the same direction. A similar analysis shows that the force is repulsive between currents in opposite directions.

This field is uniform from the wire 1 and perpendicular to it, so the force F_2 it exerts on a length **l** of wire 2 is given by $F = IlB\, sin\,\theta$ with $sin\,\theta = 1$:

$$F_2 = I_2 l B_1. \tag{7.9.23}$$

The forces on the wires are equal in magnitude, so we just write **F** for the magnitude of F_2 (Note that $\vec{F}_1 = -\vec{F}_2$.) Since the wires are very long, it is convenient to think in terms of **F/l**, the force per unit length. Substituting the expression for B_1 into Equation 7.9.23 and rearranging terms gives

Note

$$\frac{F}{l} = \frac{\mu_0 I_1 I_2}{2\pi r}. \tag{7.9.24}$$

The ratio **F/l** is the force per unit length between two parallel currents I_1 and I_2 separated by a distance **r**. The force is attractive if the currents are in the same direction and repulsive if they are in opposite directions.

This force is responsible for the **pinch effect** in electric arcs and other plasmas. The force exists whether the currents are in wires or not. It is only apparent if the overall charge density is zero; otherwise, the Coulomb repulsion overwhelms the magnetic attraction. In an electric arc, where charges are moving parallel to one another, an attractive force squeezes currents into a smaller tube. In large circuit breakers, such as those used in neighborhood power distribution systems, the pinch effect can concentrate an arc between plates of a switch trying to break a large current, burn holes, and even ignite the equipment. Another example of the pinch effect is found in the solar plasma, where jets of ionized material, such as solar flares, are shaped by magnetic forces.

The definition of the **ampere** is based on the force between current-carrying wires. Note that for long, parallel wires separated by 1 meter with each carrying 1 ampere, the force per meter is

$$\frac{F}{l} = \frac{(4\pi \times 10^{-7} T \cdot m/A)(1\,A)^2}{(2\pi)(1\,m)} = 2 \times 10^{-7}\,N/m. \tag{7.9.25}$$

Since μ_0 is exactly $4\pi \times 10^{-7}\,T \cdot m/A$ by definition, and because $1\,T = 1\,N/(A \cdot m)$, the force per meter is exactly $2 \times 10^{-7}\,N/m$. This is the basis of the definition of the ampere.

Infinite-length wires are impractical, so in practice, a current balance is constructed with coils of wire separated by a few centimeters. Force is measured to determine current. This also provides us with a method for measuring the coulomb. We measure the charge that flows for a current of one ampere in one second. That is, $1\,C = 1\,A \cdot s$. For both the ampere and the coulomb, the method of measuring force between conductors is the most accurate in practice.

Example 7.9.4: Calculating Forces on Wires

Two wires, both carrying current out of the page, have a current of magnitude 5.0 mA. The first wire is located at (0.0 cm, 3.0 cm) while the other wire is located at (4.0 cm, 0.0 cm) as shown in Figure 7.9.2. What is the magnetic force per unit length of the first wire on the second and the second wire on the first?

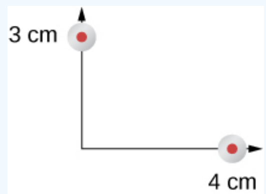


Figure 7.9.10: Two current-carrying wires at given locations with currents out of the page.

Strategy

Each wire produces a magnetic field felt by the other wire. The distance along the hypotenuse of the triangle between the wires is the radial distance used in the calculation to determine the force per unit length. Since both wires have currents flowing in the same direction, the direction of the force is toward each other.

Solution

The distance between the wires results from finding the hypotenuse of a triangle:

$$r = \sqrt{(3.0\,cm)^2 + (4.0\,cm)^2} = 5.0\,cm. \tag{7.9.26}$$

The force per unit length can then be calculated using the known currents in the wires:

$$\frac{F}{l} = \frac{(4\pi \times 10^{-7} T \cdot m/A)(5 \times 10^{-3} A)^2}{(2\pi)(5 \times 10^{-2} m)} = 1 \times 10^{-10}\,N/m. \tag{7.9.27}$$

The force from the first wire pulls the second wire. The angle between the radius and the **x**-axis is

$$\theta = tan^{-1}\left(\frac{3\,cm}{4\,cm}\right) = 36.9^o. \tag{7.9.28}$$

The unit vector for this is calculated by

$$cos(36.9^o)\hat{i} - sin(36.9^o)\hat{j} = 0.8\hat{i} - 0.6\hat{j}. \tag{7.9.29}$$

Therefore, the force per unit length from wire one on wire 2 is

$$\frac{\vec{F}}{l} = (1 \times 10^{-10}\,N/m) \times (0.8\hat{i} - 0.6\hat{j}) = (8 \times 10^{-11}\hat{i} - 6 \times 10^{-11}\hat{j})\,N/m. \tag{7.9.30}$$

The force per unit length from wire 2 on wire 1 is the negative of the previous answer:

$$\frac{\vec{F}}{l} = (-8 \times 10^{-11}\hat{i} + 6 \times 10^{-11}\hat{j})N/m. \tag{7.9.31}$$

Significance

These wires produced magnetic fields of equal magnitude but opposite directions at each other's locations. Whether the fields are identical or not, the forces that the wires exert on each other are always equal in magnitude and opposite in direction (Newton's third law).

? Exercise 7.9.4

Two wires, both carrying current out of the page, have a current of magnitude 2.0 mA and 3.0 mA, respectively. The first wire is located at (0.0 cm, 5.0 cm) while the other wire is located at (12.0 cm, 0.0 cm). What is the magnitude of the magnetic force per unit length of the first wire on the second and the second wire on the first?

Answer

Both have a force per unit length of $9.23 \times 10^{-12}\ N/m$

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