General Physics 2 Q3 Week 8

Integrated Science (Philippine Science High School System)

DEPARTMENT OF EDUCATION
SCHOOLS DIVISION OF NEGROS ORIENTAL
REGION VII
Kagawasan Ave., Daro, Dumaguete City, Negros Oriental

BIOT-SAVART LAW AND AMPERE'S LAW

for GENERAL PHYSICS 2/ Grade 12/ Quarter 3/ Week 8

SELF-LEARNING KIT

NegOr_Q3_GenPhysics2_SLKWeek8_v2

FOREWORD

In this self-learning kit, you will be able to demonstrate an understanding about Biot-Savart Law and Ampere's Law. The writers make sure that the lesson will be interactive as it is not just a module but something you can learn and discover new concepts and ideas and at the same time enjoy.

OBJECTIVES

At the end of this Self-Learning Kit, you should be able to:

K: define Biot-Savart Law;

S: use Biot-Savart Law to calculate the magnetic field due to one or more straight wire conductors;

: use Ampere's Law to solve problems involving magnetic fields, forces due to magnetic fields and the motion of charges and current-carrying wires; and

A: appreciate the importance of the topic by applying the concepts to solve physics problem correctly.

LEARNING COMPETENCIES

Evaluate the magnetic field vector at a given point in space due to a moving point charge, an infinitesimal current element, or a straight current-carrying conductor **(STEM_GP12EMIIIh-60).**

Calculate the magnetic field due to one or more straight wire conductors using the superposition principle **(STEM_GP12EMIIIi-62).**

Calculate the force per unit length on a current carrying wire due to the magnetic field produced by other current-carrying wires **(STEM_GP12EMIIIi-63).**

Evaluate the magnetic field vector at any point along the axis of a circular current loop **(STEM_GP12EMIIIi-64).**

Solve problems involving magnetic fields, forces due to magnetic fields and the motion of charges and current-carrying wires in contexts such as, but not limited to, determining the strength of Earth's magnetic field, mass spectrometers, and solenoids **(STEM_GP12EMIIIi-66).**

I. WHAT HAPPENED

PRE-TEST

TRUE OR FALSE: Read each statement carefully. Write ***TRUE*** if the statement is correct, and ***FALSE*** if it is wrong. Write your answers in your notebook/Answer Sheet.

1. The Biot Savart Law is an equation describing the magnetic field generated by a constant electric field.
2. Biot–Savart law is consistent with both Ampere's circuital law and Gauss's theorem.

3. The Biot Savart law is fundamental to magnetostatics.
4. Biot-Savart law was created by two French physicists, Jean Baptiste Biot and Felix Savart.
5. The mathematical expression for magnetic flux density was derived by Biot-Savart in 1825.
6. Gauss's Law allowed us to find the net electric field due to any charge distribution by applying symmetry.
7. Ampere's Law is a useful law that relates the net magnetic field along a closed loop to the electric field current passing through the loop.
8. All currents have to be steady and do not change with time.
9. Current have to be taken with their algebraic sign by using the Right-Hand Rule.
10. Ampere's Law was first discovered by André-Marie Ampère in1825.

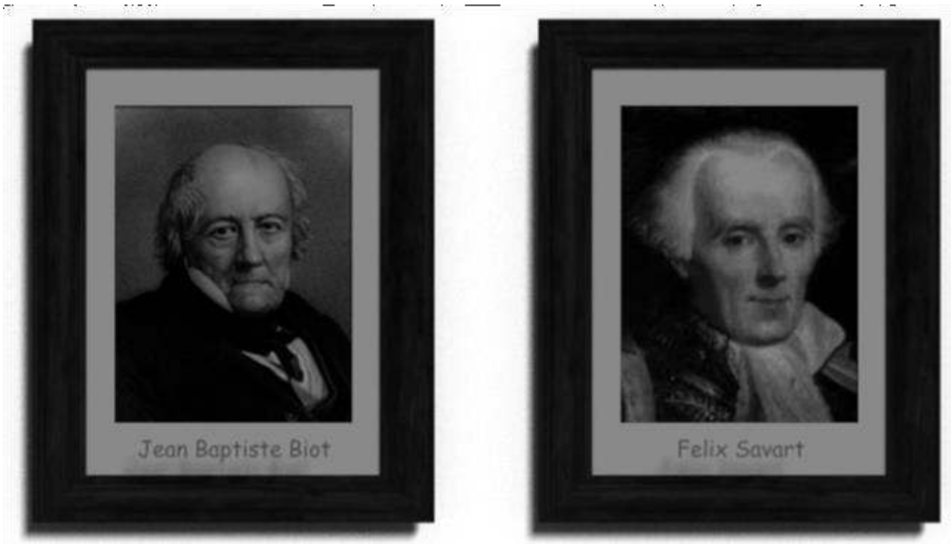
II. WHAT I NEED TO KNOW
DISCUSSION

BIOT-SAVART LAW

What is Biot-Savart Law?

The Biot Savart Law is an equation describing the magnetic field generated by a constant electric current. It relates the magnetic field to the magnitude, direction, length, and proximity of the electric current. Biot–Savart law is consistent with both Ampere's circuital law and Gauss's theorem. The Biot Savart law is fundamental to magnetostatics, playing a role similar to that of Coulomb's law in electrostatics.

Biot-Savart law was created by two French physicists, Jean Baptiste Biot and Felix Savart derived the mathematical expression for magnetic flux density at a point due to a nearby current-carrying conductor, in 1820. Viewing the deflection of a magnetic compass needle, these two scientists concluded that any current element projects a magnetic field into the space around it.



Adapted from https://www.electrical4u.com/wp-content/uploads/Jean-Baptiste-Biot-Felix-Savart.png

***Figure 1*. Pictures of Jean Baptiste Biot on the left and Felix Savart on the right**

Through observations and calculations, they had derived a mathematical expression, which shows, the magnetic flux density of which dB, is directly proportional to the length of the element dl, the current I, the sine of the angle and θ between the direction of the current and the vector joining a given point of the magnetic field and the current element and is inversely proportional to the square of the distance of the given point from the current element, r.

Biot Savart Law Statement & Derivation

The **Biot-Savart law** can be stated as:

$$\text{Hence, } dB \propto \frac{Idlsin\theta}{r^2} \text{ or } dB = k\frac{Idlsin\theta}{r^2}$$

Where, ***k*** is a constant, depending upon the magnetic properties of the medium and system of the units employed. In the SI system of unit,

$$k = \frac{\mu_o \mu_r}{4\pi}$$

Therefore, the final **Biot-Savart law derivation** is,

$$dB = \frac{\mu_o \mu_r}{4\pi} \times \frac{Idlsin\theta}{r^2}$$

Let us consider a long wire carrying a current I and also consider a point p in the space. The wire is presented in the picture below, by red color.

Let us also consider an infinitely small length of the wire dl at a distance r from the point *P* as shown. Here, *r* is a distance-vector which makes an angle θ with the direction of current in the infinitesimal portion of the wire.

If you try to visualize the condition, you can easily understand the magnetic field density at point P due to that infinitesimal length dl of the wire is directly proportional to current carried by this portion of the wire.

As the current through that infinitesimal length of wire is the same as the current carried by the whole wire itself, we can write,

$$dB \propto I$$

It is also very natural to think that the magnetic field density at that point P due to that infinitesimal length dl of wire is inversely proportional to the square of the straight distance from point P to the center of dl. Mathematically we can write this as,

$$dB \propto \frac{1}{r^2}$$

Lastly, magnetic field density at that point P due to that infinitesimal portion of the wire is also directly proportional to the actual length of the infinitesimal length dl of wire.

As θ be the angle between distance vector r and d direction of current through this infinitesimal portion of the wire, the component of dl directly facing perpendicular to the point P is dl sin θ,

$$\text{Hence, } dB \propto dl \sin\theta$$

Now, combining these three statements, we can write,

$$dB \propto \frac{I.dl.sin\theta}{r^2}$$

This is the basic form of **Biot–Savart's Law**

Now, putting the value of constant k (which we have already introduced at the beginning of this SLK) in the above expression, we get

$$dB \propto k\frac{I.dl.sin\theta}{r^2}$$

$$\Rightarrow dB = \frac{\mu_0 \mu_r}{4\pi}$$

Here, μ_0 used in the expression of constant k is absolute permeability of air or vacuum and its value is $4\pi 10^{-7}$ W_b/ A-m in the SI system of units. μr of the expression of constant k is the relative permeability of the medium.

Now, flux density(B) at the point P due to the total length of the current-carrying conductor or wire can be represented as,

$$B = \int dB = dB = \int \frac{\mu_0 \mu_r}{4\pi} \times \frac{Idl sin\theta}{r^2} = \frac{\mu_0 \mu_r}{4\pi} \int \frac{sin\theta}{r^2} dl$$

If D is the perpendicular distance of the point P from the wire, then

$$r sin\theta = D \text{ or } r = \frac{D}{sin\theta}$$

Now, the expression of flux density B at point P can be rewritten as,

$$B = \frac{I\mu_0 \mu_r}{4\pi} \int \frac{sin\theta}{r^2} dl = \frac{I\mu_0 \mu_r}{4\pi} \int \frac{sin^3\theta}{D^2} dl$$

Again, $\frac{l}{D} = cot\theta \Rightarrow l = D\ cot\theta$

Therefore, $dl = -D cosec^2\theta d\theta$

Finally, the expression of B comes as,

$$B = \frac{I\mu_0 \mu_r}{4\pi} \int \frac{sin^3\theta}{D^2} [-D cosec^2\theta d\theta$$

$$= - \frac{I\mu_0 \mu_r}{4\pi D} \int sin^3\theta cosec^2\theta d\theta$$

$$= - \frac{I\mu_0 \mu_r}{4\pi D} \int sin\theta d\theta$$

This angle θ depends upon the length of the wire and the position of the point P. Say for a certain limited length of the wire, angle θ as indicated in the figure above varies from $\theta 1$ to $\theta 2$. Hence, magnetic flux density at point P due to the total length of the conductor is,

$$B = - \frac{I\mu_0 \mu_r}{4\pi D} \int_{\theta 1}^{\theta 2} sin\theta d\theta$$

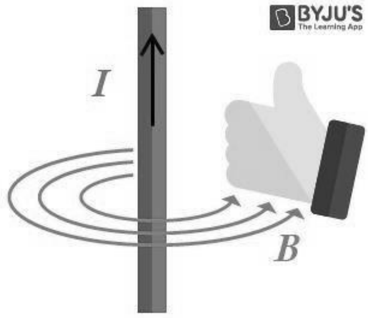
$$= - \frac{I\mu_0 \mu_r}{4\pi D} [-cos\theta]_{\theta 1}^{\theta 2}$$

$$= \frac{I\mu_0 \mu_r}{4\pi D} [\cos \theta_1 - cos\theta_2]$$

Let's imagine the wire is infinitely long, then θ will vary from 0 to π that is $\theta_1 = 0$ to $\theta_2 = \pi$. Putting these two values in the above final expression of **Biot Savart law**, we get,

$$B = \frac{I\mu_0\mu_r}{4\pi D}\left[\cos 0 - cos\pi\right] = \frac{I\mu_0\mu_r}{4\pi D}\;[1 - (-1)]$$

The direction of the magnetic field is always in a plane perpendicular to the line of element and position vector. It is given by the right-hand thumb rule where the thumb points to the direction of conventional current and the other fingers show the magnetic field's direction (See Figure 2).

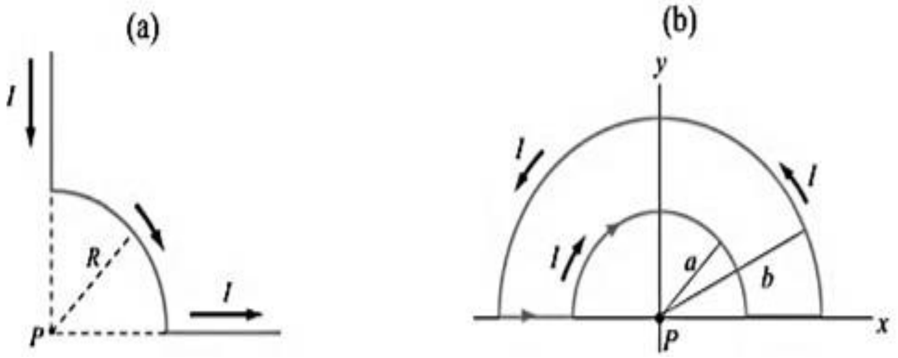


Adapted from https://cdn1.byjus.com/wp-content/uploads/2018/11/physics/wp-content/uploads/2016/01/biot-savart-law-02.jpg

Figure 2. In the figure shown above, the direction of the magnetic field is pointing into the page

Example Problem 1:

Find the magnetic field at point P due to the following current distributions:



Solution:

a. The fields due to the straight wire segments are zero at P because d G s and rˆ are parallel or anti-parallel. For the field due to the arc segment, the magnitude of the magnetic field due to a differential current carrying element is given in this case by

$$d\vec{\mathbf{B}} = \frac{\mu_0 I}{4\pi}\frac{d\vec{\mathbf{s}}\times\hat{\mathbf{r}}}{R^2} = \frac{\mu_0}{4\pi}\frac{IRd\theta(\sin\theta\,\hat{\mathbf{i}} - \cos\theta\,\hat{\mathbf{j}})\times(-\cos\theta\,\hat{\mathbf{i}} - \sin\theta\,\hat{\mathbf{j}})}{R^2}$$

$$= -\frac{\mu_0}{4\pi}\frac{I(\sin^2\theta + \cos^2\theta)d\theta}{R}\hat{\mathbf{k}} = -\frac{\mu_0}{4\pi}\frac{Id\theta}{R}\hat{\mathbf{k}}$$

Therefore,

$$\vec{\mathbf{B}} = -\int_0^{\pi/2}\frac{\mu_0 I}{4\pi R}d\theta\,\hat{\mathbf{k}} = -\frac{\mu_0 I}{4\pi R}\left(\frac{\pi}{2}\right)\hat{\mathbf{k}} = -\left(\frac{\mu_0 I}{8R}\right)\hat{\mathbf{k}} \text{ (or, into the page).}$$

b. There is no magnetic field due to the straight segments because point P is along the G lines. Using the general expression for dB obtained in (a), for the outer segment, we have

$$\vec{\mathbf{B}}_{out} = \int_0^{\pi}\frac{\mu_0}{4\pi}\frac{Id\theta}{b}\hat{\mathbf{k}} = \left(\frac{\mu_0 I}{4b}\right)\hat{\mathbf{k}}$$

Similarly, the contribution to the magnetic field from the inner segment is

$$\vec{\mathbf{B}}_{in} = \int_{\pi}^{0}\frac{\mu_0}{4\pi}\frac{Id\theta}{a}\hat{\mathbf{k}} = -\left(\frac{\mu_0 I}{4a}\right)\hat{\mathbf{k}}.$$

Therefore,

$$\vec{\mathbf{B}}_{net} = \vec{\mathbf{B}}_{out} + \vec{\mathbf{B}}_{in} = -\frac{\mu_0 I}{4}\left(\frac{1}{a} - \frac{1}{b}\right)\hat{\mathbf{k}} \text{ (into the page since } a < b\text{).}$$

Example Problem 2:

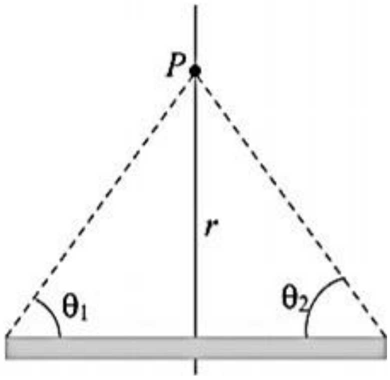
A conductor in the shape of a square loop of edge length ℓ = 0.400 m carries a current I = 10.0 A as in the figure.

(a) Calculate the magnitude and direction of the magnetic field at the center of the square.

(b) If this conductor is formed into a single circular turn and carries the same current, what is the value of the magnetic field at the center?

Solution:

For a finite wire carrying a current I, the contribution to the magnetic field at a point *P* is



$$B = \frac{\mu_0 I}{4\pi r}(\cos\theta_1 + \cos\theta_2)$$

where θ_1 and θ_2 are the angles which parameterize the length of the wire.

Consider the bottom segment. The cosine of the angles are given by

$$\cos\theta_2 = \cos\theta_1 = \cos 45° = \frac{1}{\sqrt{2}}$$

This leads to

$$B_1 = \frac{\mu_0 I}{4\pi(l/2)}\left(\frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}}\right) = \frac{\mu_0 I}{\sqrt{2}\pi l}$$

The direction of B_1 is into the page. One may show that the other three segments yield the same contribution. Therefore, the total magnetic field at P is

$$B = 4B_1 = 2\sqrt{2}\frac{\mu_0 I}{\pi l} = 2\sqrt{2}\frac{(4\pi\times10^{-7}\,\mathrm{T\cdot m/A})(10\,\mathrm{A})}{\pi(0.40\,\mathrm{m})} = 2.83\times10^{-5}\,\mathrm{T}\text{ (into the page)}$$

AMPERE’S LAW

Ampere’s Law is a useful law that relates the net magnetic field along a closed loop to the electric field current passing through the loop. It is first discovered by André-Marie Ampère in 1826.

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Figure 3. Pictures of André-Marie Ampèr

André Ampère formulated a law based on Oersted’s as well as his own experimental studies. This law can be regarded as an s alternative expression of Biot-savert’s law which also relates the magnetic field and current produced. But it needed an exclusive calculation of the curl of B. And that calculation, leads to the limitation of the usual form of this law i.e. its validity holding only for steady currents.

After four decades later, the James Clerk Maxwell realized that the equation provided by the Ampere was incomplete, and extended his law by including that the magnetic field arises due to the electric current by giving a mathematical formulation.

Ampere’s Law Statement

Ampere’s circuital law states: *The line integral of the magnetic field, over a closed path, or loop, equals times the total current enclosed by that closed loop.* We express this law through the mathematical expression:

Line Integral

Permeability of free space

$$\oint \vec{B}.\vec{ds} = \mu_0 I_{enc}$$

B.ds is integrated around a closed loop called Amperian Loop

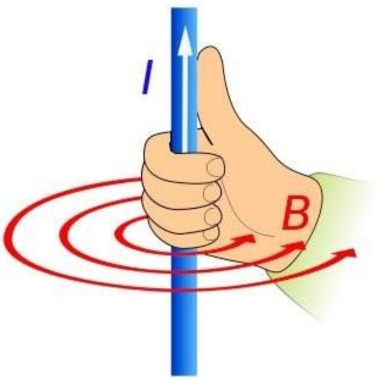
Enclosed current by the curved

Where μ_o = permeability of free space = $4\pi\times10^{-15}$ N/A^2

Important Notes

- All currents have to be steady and do not change with time.
- Only currents crossing the area inside the path are taken into account.
- Current have to be taken with their algebraic sign by using the Right Hand Rule

The Right-hand Rule for Determining the Direction of Magnetic Field



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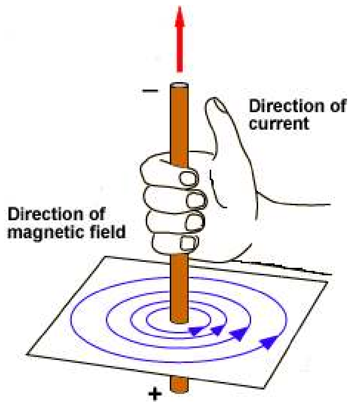

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The right hand rule states that: *to determine the direction of the magnetic force on a positive moving charge, point your right thumb in the direction of the velocity (v), your index finger in the direction of the magnetic field (B), and your middle finger will point in the direction of the resulting magnetic force (F).* Negative charges will be affected by a force in the opposite direction.

Applications:

Magnetic Field Inside A Long Cylindrical Conductor

A cylindrical conductor with radius R carries a current I. The current is uniformly distributed over the cross-sectional area of the conductor. Find the magnetic field as a function of the distance r from the conductor axis for points both inside *(r<R)* and outside *(r>R)* the conductor.

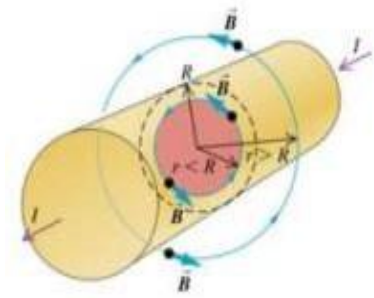
From Ampere's Law, we have:

$$\oint B.ds=\mu_o I$$

We will take the ampere loop to be a circle. Hence, for points inside the conductor, the ampere loop will be a circle with radius r, where $r<R$. The current enclosed will be $\frac{I}{R^2}\ x\ \pi r^2$

$$2\pi r = \mu_o \frac{}{\pi R^2} \quad \pi r^2$$

$$= \frac{\mu_o}{2\pi} \frac{r}{R^2}$$



For points outside the conductor, the ampere loop will be a circle of radius r, where $r>R$. The current enclosed will just be I.

Magnetic Field of a Solenoid

A solenoid consists of a helical winding of wire on a cylinder, usually circular in cross section. If the solenoid is long in comparison with its cross-sectional diameter and the coils are tightly wound, the internal field near the midpoint of the solenoid's length is very nearly uniform over the cross section and parallel to the axis, and the external field near the midpoint is very small. Use Ampere's law to find the field at or near the center of such a long solenoid. The solenoid has n turns of wire per unit length and carries a current I.

From Ampere's Law, we have:

$$\oint \vec{B}.d\vec{l} = \mu_0 I_{encl}$$

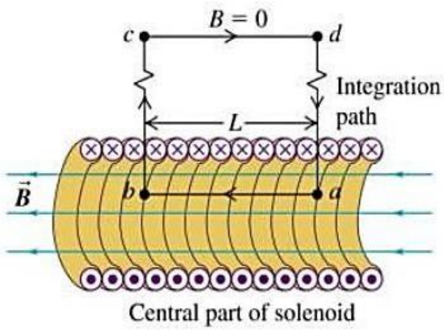
Following the integration path, we have:

$$\oint \vec{B}.d\vec{l} = \mu_0 nLI$$

$$\int_a^b \vec{B}.d\vec{l} + \int_b^c \vec{B}.d\vec{l} + \int_c^d \vec{B}.d\vec{l} + \int_d^a \vec{B}.d\vec{l} = \mu_0 nLI$$

$$BL + 0 + 0 + 0 = \mu_0 nLI$$

$$B = \mu_0 nI$$

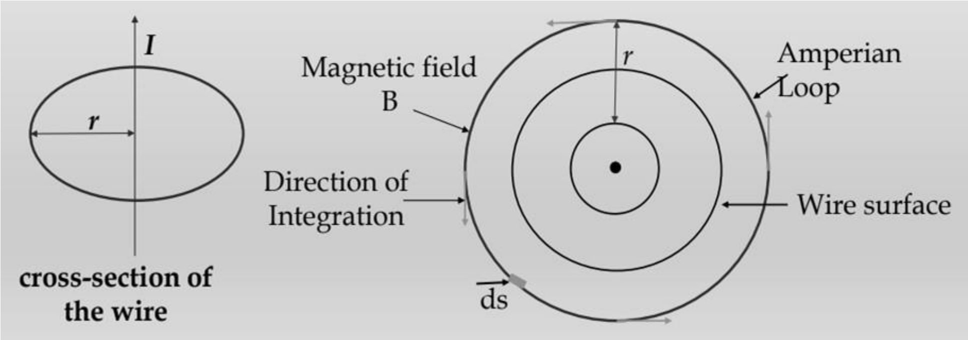


Limitations

The limitation of Ampere's law is that it is valid only for steady current. The conventional form of Ampere's circuital law was pointed out by Maxwell. He introduced the concept of displacement currents (currents associated with time varying electric fields) to generalize Ampere's Circuital law even for non-steady currents. It was this generalization (of Ampere's circuital law) that played a crucial and central role in the development of Maxwell's electromagnetic theory of light.

Example Problem 3:

Find the magnetic field outside a long straight wire with current I and radius r.

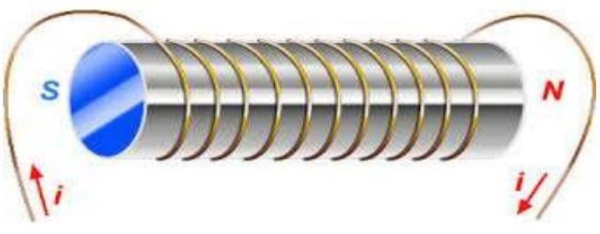


Solution:

$$\oint B.ds = \mu_0 I$$
$$B \oint ds = \mu_0 I$$
$$B(2\pi r) = \mu_0 I$$
$$ds = 2\pi r \rightarrow circumference\ of\ a\ circle$$
$$B = \frac{\mu_0 I}{2\pi r}$$

Example Problem 4:

What is the direction of magnetic field due to a current passing through a solenoid? (Remember to use the Right Hand Rule where the thumb takes the direction of the current.)



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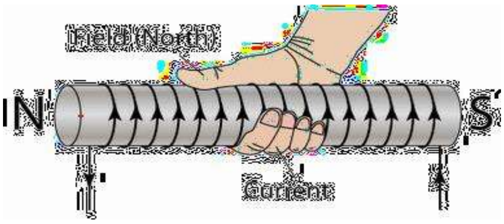
Answer:

Right-hand rule can be used to find the direction of the magnetic field. In this case, point the wrapped fingers (along the coil) in the direction of the conventional current. Then, the thumb will point to the direction of magnetic field within the solenoid.



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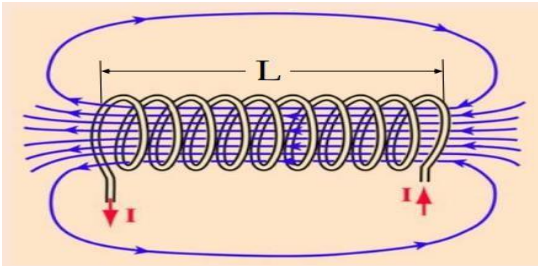
Example Problem 5:

Use Ampere's Law to determine the magnetic field strength outside a solenoid with n turns (coils) per unit length.



Solution:

$\oint B.ds = \mu_o I$

$B\oint ds = \mu_o I$

$ds = L \rightarrow$ ***total length of the wire(solenoid)***

$\boldsymbol{I \rightarrow nI}$ ***amount of current due to number of turn***

$(L) = \mu_o \boldsymbol{nI}$

$\therefore \boldsymbol{B = \mu_o nI\ L} \rightarrow$ ***magnetic field in a solenoid***

PERFORMANCE TASK:

Directions: Read the given situation below and answer the question that follows. Do this in your notebook/Activity Sheet.

- In a geology class, you were asked to determine miniscule pieces of rocks are magnetic or not. The problem is you don't have available magnets in the laboratory but few copper wires and a power supply. How will you identify the magnetic property of rocks?

IV. WHAT I HAVE LEARNED
POST TEST/EVALUATION

A. MODIFIED TRUE OR FALSE: Write the word ***True*** if the statement is correct, otherwise, write the word which makes the statement wrong and indicate the correct word opposite to it. Do this in your notebook/Activity Sheet.

1. Biot Savart Law is an equation describing the magnetic field generated by a constant electric current.
2. Biot–Savart law is consistent with both Snell's law and Gauss's theorem.
3. The Biot Savart law is fundamental to magnetostatics.
4. Biot-Savart law was created by two French physicists, Jean Baptiste Biot and Felix Savart.
5. The mathematical expression for magnetic flux density was derived by Biot-Savart in 1920.

B. PROBLEM SOLVING: Read each problem carefully. Write the solutions on your notebook.

1. A circular coil of radius 5×10^{-2} m and with 40 turns is carrying a current of 0.25 A. Determine the magnetic field of the circular coil at the center.
2. Determine the magnetic field at the center of the semicircular piece of wire with radius 0.20 m. The current carried by the semicircular piece of wire is 150 A.
3. The magnetic field strength of a solenoid is 0.0270T. Its radius is 0.40 m and length is 0.40 m. How many turns are there in the solenoid if the steady current passing through it is 12.0 A?

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DEPARTMENT OF EDUCATION
SCHOOLS DIVISION OF NEGROS ORIENTAL

SENEN PRISCILLO P. PAULIN, CESO V
Schools Division Superintendent

JOELYZA M. ARCILLA EdD
OIC - Assistant Schools Division Superintendent

MARCELO K. PALISPIS EdD JD
OIC - Assistant Schools Division Superintendent

NILITA L. RAGAY EdD
OIC - Assistant Schools Division Superintendent/CID Chief

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PSDS - Division Science Coordinator

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ELMAR L. CABRERA
PDO II (LRMDS)

GIL S. DAEL
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Writers

STEPHEN C. BALDADO
Lay-out Artist

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ROWENA R. DINOKOT
GENEVA FAYE L. MENDOZA

BETA QA TEAM
ZENAIDA A. ACADEMIA
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LESTER C. PABALINAS

SYNOPSIS AND ABOUT THE AUTHORS

Biot-Savart's law is an equation that gives the magnetic field produced due to a current carrying segment. This segment is taken as a vector quantity known as the current element. We can use Biot–Savart law to calculate magnetic responses even at the atomic or molecular level. It is also used in aerodynamic theory to calculate the velocity induced by vortex lines. Biot-Savart law is similar to the Coulomb's law in electrostatics. The law is applicable for very small conductors too which carry current. It is also applicable for symmetrical current distribution.

Ampere's Law is a useful law that relates the net magnetic field along a closed loop to the electric field current passing through the loop. Ampere's circuital law states: The line integral of the magnetic field, over a closed path, or loop, equals times the total current enclosed by that closed loop. It is very important to remember that all currents have to be steady and do not change with time. Only currents crossing the area inside the path are taken into account. And finally, current have to be taken with their algebraic sign by using the Right Hand Rule.

Mr. Jose Mari B. Acabal finished his Bachelor's Degree in Secondary Education at NORSU-Bais major in Biological Sciences in 2015. He also finished his Masters Degree in Education major in General Science at Foundation University in October 2019. Currently, he is a Teacher 3 at Panciao High School of Manjuyod District 1 in the Division of Negros Oriental.

Gil S. Dael earned h
Mathematics degree and M
Mathematics graduate progra
University. He is presently finishi
Mathematics from the same U
currently teaching Mathematic
Crisostomo O. Retes National H

Pre-Test:

1. FALSE
2. TRUE
3. TRUE
4. TRUE
5. FALSE
6. TRUE
7. TRUE
8. TRUE
9. TRUE
10. FALSE

Post-Test:

A. Modified True or False:

1. TRUE
2. Snell's Law -Ampere's Circuital Law
3. TRUE
4. TRUE
5. 1920-1820