Electrical Tech Note — 217

Biosystems & Agricultural Engineering Department
Michigan State University

Magnetism

There is a relationship between current flow through a conductor and a magnetic field flux that builds up around the conductor. This *Tech Note* explores this relationship and discusses various useful applications. Magnetic flux has a direction which is dependant upon the direction electrical charges flow in a conductor. It is important to define the direction of electrical current flow in order to define the direction of the magnetic flux.

Conventional Current Flow: *Conventional current flow assumes current is flowing from the positive terminal to the negative terminal.* The negative (–) terminal of an electrical supply provides electrons which are available to flow through a conductor. The positive (+) terminal attracts the free electrons. When electricity flows through a conductor electrons are actually flowing from the negative (–) terminal to the positive (+) terminal. *The flow of electrical current through a conductor is actually the flow of electrical charge, (-) in one direction and an equal flow of positive charge flowing in the opposite direction through the conductor.* This is illustrated in *Figure 217.1.* When a negative charge (–) moves in one direction through a conductor an equal quantity of positive charge (+) moves in the opposite direction. The flow of electricity in a conductor is a flow of charges simultaneously all through the conductor from one end to the other.

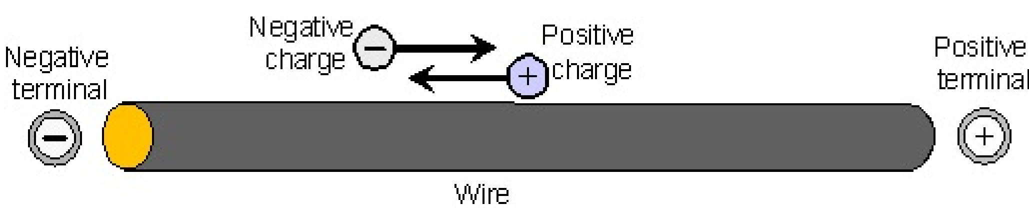

Figure 217.1 *Electrical current flow through a conductor is actually a flow of negative charges in one direction and positive charges flowing in the opposite direction.*

Note in *Figure 217.1* the electrical current flow is actually positive charges flowing in one direction and negative charges flowing in the opposite direction. The flow of electricity through a conductor can, therefore, be defined as flowing from positive (+) to negative (–), or it can be defined as flowing from negative (–) to positive (+).

Some text books define electrical current flow from negative to positive because that is the direction of electron flow through the conductor. There are two flows of electrical charge, plus and minus, flowing at the same time but in opposite directions. Some text books define electrical current flow from negative to positive and others define current flow from positive to flow negative. This creates confusion for the reader. It is necessary to define a direction of current flow because current flow creates a magnetic field and magnetic field has a direction. Engineers and scientists have defined *conventional current* flow based upon a positive charge flowing from the positive terminal (+) to the negative terminal (–) as illustrated in *Figure 217.2.*

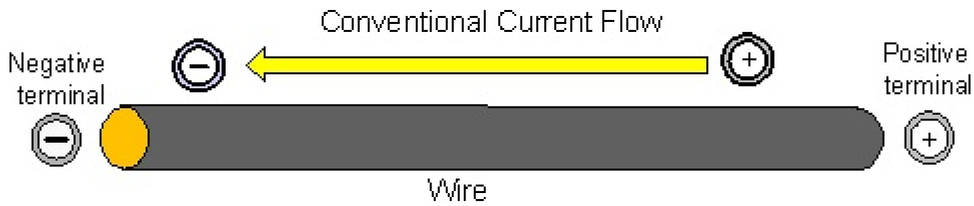

Figure 217.2 *Conventional current flow as defined by engineers and scientists is from positive to negative.*

Magnetic Flux: Natural magnets are materials which have the ability to exert forces on each other and upon some other materials such as iron. A magnet is surrounded by a magnetic field. The forces produced by a magnet are strong next to the magnet and grow weaker at greater distances from the magnet. This magnetism created by the magnet is called *magnetic flux*. The *Weber* is the unit of measure of magnetic flux. What is of real significance is the amount of magnetic flux that is concentrated into a given space. This is called *magnetic flux density and a common unit of measure of magnetic flux density is Webers per square meter (Weber/m^2) or Tesla*. One Weber per square meter is equal to one Tesla. Another unit for of measure of magnetic flux density is the Gauss. *The symbol for magnetic flux density is **B**.* One Weber per square meter is equal to 10,000 *Gauss*.

The unit of magnetic flux (*Webers)* is also defined as torque per Ampere. Torque is in units of *Newton-meters*, therefore, the *Weber* is equal to *one Newton-meter per Ampere*. Since power is torque per unit time, then power is proportional to current flow. These conversions are summarized as follows:

1 Weber/m^2 = 10,000 Gauss = 1 Tesla

$$1 \text{ Weber} = \frac{\text{Newton-meters}}{\text{Ampere}}$$

where Newton-meters is torque

$$\text{therefore,} \quad 1 \text{ Weber} = \frac{\text{torque}}{\text{Ampere}}$$

Magnetic flux has a direction or an orientation in relation to the poles of the magnet. Magnetic poles are defined as North (N) and South (S) as shown in *Figure 217.3.* Within the magnet the magnetic flux is oriented from South (S) to North (N). *On the outside of the magnet the flux is oriented from North (N) to South (S).* This is important to know because these are the forces that operate solenoids and electric motors.

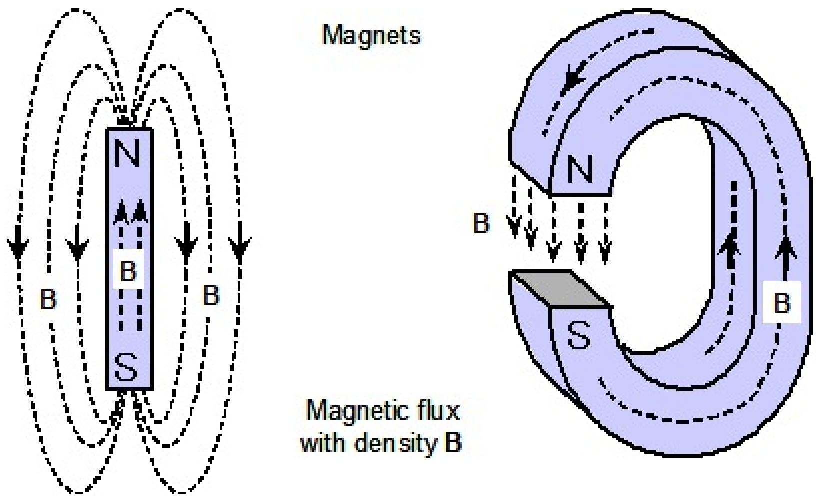

Figure 217.3 *Magnetic flux completes a circuit with the direction from South to North inside the magnet and from North to South outside the magnet.*

H. C. Oersted in 1820 discovered that electrical current flow in a wire produced a magnetic field around the wire. This is illustrated in *Figure 217.4.* Later, A. M. *Ampere developed a mathematical theory which quantitatively described the relationship between the magnetic flux density and the current flow in the conductor.* This is known as ***Ampere's law***. The equation involves the use of calculus and will not be discussed in this Tech Note.

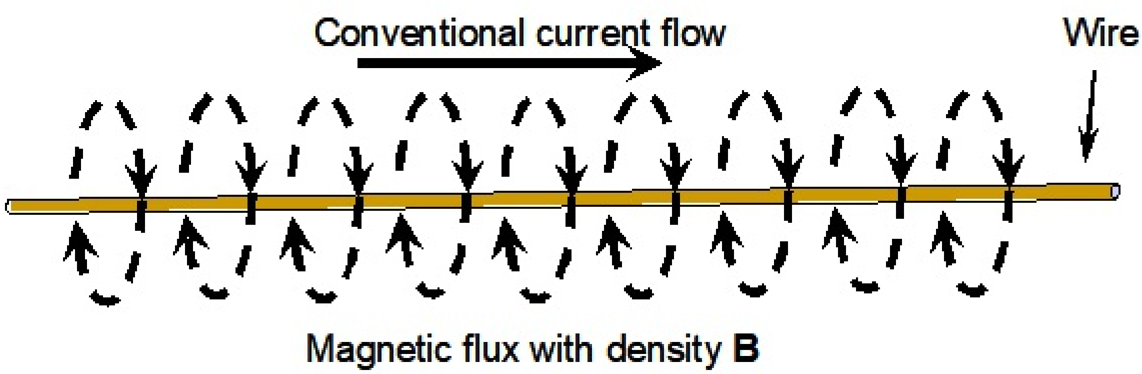

Figure 217.4 *Electrical current flow through a wire creates a magnetic field around the wire.*

The orientation of the magnetic flux around a wire carrying current (conventional current) can be found in *Ampere's law*. This is known as the ***Right Hand Rule.*** *Grasp the wire with the right hand with the thumb pointing in the direction of the conventional current flow. The fingers of the right hand will curl around the wire with the tips of the fingers pointing in the direction of the magnetic flux.* This is illustrated in *Figure 217.5.* (Text books using electron flow will call this the left hand rule)

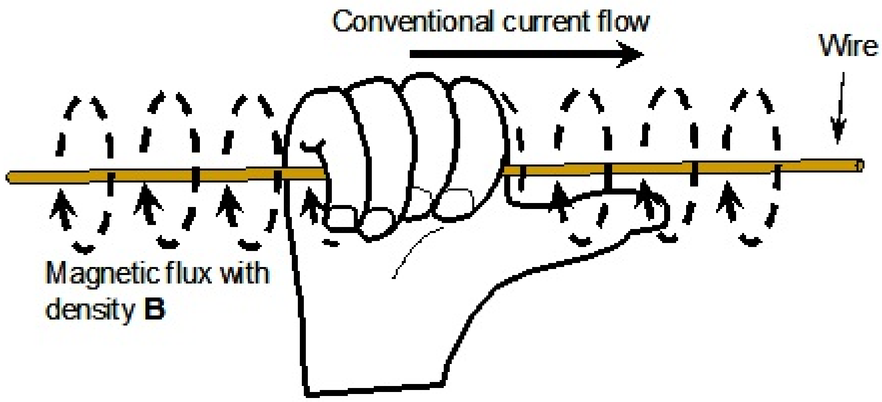

Figure 217.5 *Grasp the wire with the right hand with the thumb pointing in the direction of the current flow and the fingers will curl around the conductor in the direction of the magnetic flux.*

Electromagnets: If there is a magnetic field around a wire carrying electrical current, then it would seem reasonable that an electrical magnet (electromagnet) can be constructed. Imagine a coil of wire such created by wrapping insulated wire around the paper core of a roll of paper towel. Then pass current through the wire. This is illustrated in *Figure 217.6.* By defining current as flowing from positive (+) to negative (−), the rules for determining the orientation of the magnetic flux produced are **Right Hand** rules not left hand rules. Using the right hand rule the direction of magnetic flux around each wire can be obtained. Note when this is done for the coil of wire in *Figure 217.6* all of the flux arrows on the inside of the coil are pointing in the same direction. On the outside of the coil the magnetic flux arrows are also pointing in the same direction. Of course, if the current flow was in the opposite direction all the magnetic flux lines would point in the opposite direction.

Now remember from the earlier discussion that the magnetic flux points from the South pole (S) to the North pole (N) on the inside of the magnet. Therefore, the location of the magnetic North pole and the South pole of the electromagnet can be determined as shown in *Figure 217.6.*

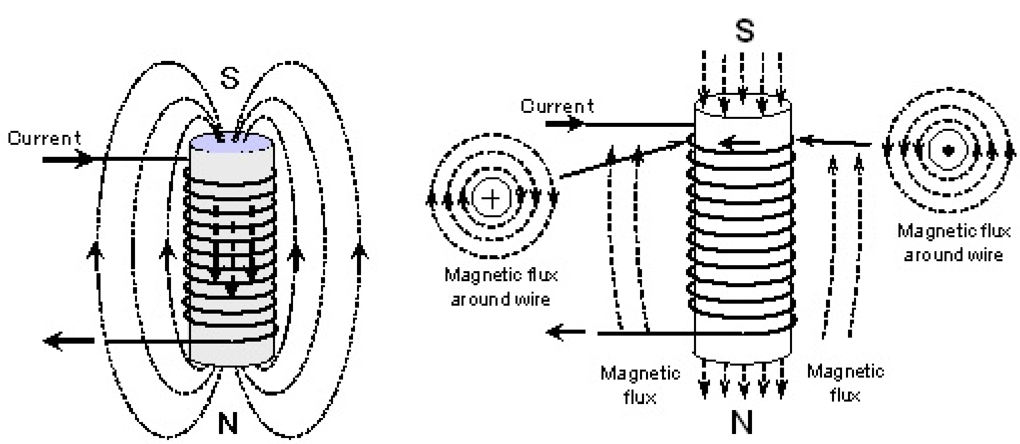

Figure 217.6 *Use the right hand rule to determine the direction of the magnetic flux of each wire in the coil. Flux is oriented South to North* <u>*inside*</u> *the magnet. When looking at a cross section of a wire a dot indicates current flowing towards the observer and a cross indicates current flowing away from the observer.*

There is another **right hand rule** which can be used to determine the poles of an electromagnet. Grasp the electromagnet with the right hand and the fingers pointing in the direction the current is flowing around the electromagnet. The thumb is then pointing to the north pole of the electromagnet. This is illustrated in *Figure 217.7.*

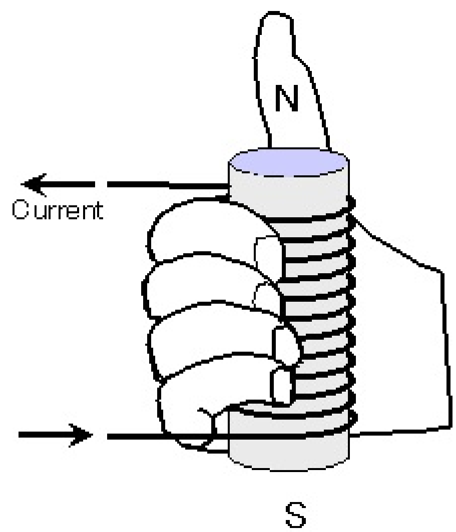

Figure 217.7 *To determine the North pole of an electromagnet, grasp the coil with the fingers coiled in the direction of current flow, and the thumb points to the North pole.*

Current Flows in a Wire Placed in a Moving Magnetic Flux: *Michael Faraday* in 1831 discovered that when a magnet is moved near a wire completing a circuit, a current flow is induced into the wire. This is illustrated in *Figure 217.8.* ***Faraday's law*** explains that *when a magnet is moved past a wire completing a circuit a current is induced into the wire*. It does not matter whether the wire is moved with the magnet stationary or vice versa. As long as the wire is moving with respect to the magnetic flux a current is induced to flow in the loop of wire. The motion of the wire must be perpendicular to the orientation of the magnetic flux.

A current induced into a wire by magnetic flux will flow through the wire in such a direction that the magnetic flux produced by the induced current will attempt to repel the original magnetic flux. This means that if a North magnetic pole is moved towards a coil of wire, the induced current flow in the coil of wire will produce a North magnetic pole to *repel* the approaching magnet. This theory was actually deduced from observations with magnets and induced currents in wire circuits by *H. F. Lenz* in 1834 and became known as *Lenz's law.* Using ***Lenz's law****, the direction of induced current flow in a wire can be determined*. *Lenz's law also describes the principle upon which an electric induction motor operates*.

Another right hand rule describes the relationship between the magnetic flux, current flow and direction of motion of the wire. *Point the* ***thumb*** *of the right hand in the direction of motion of the wire through the magnetic flux*. *Point the* ***index finger*** *in the direction of magnetic flux from North to South*. Bend the ***second finger*** so it forms a right angle to the index finger. The *second finger* is pointing in the direction of conventional current flow in the loop of wire. This is illustrated in *Figure 217.8.*

Note in *Figure 217.8* that the magnet moving to the right is the same as moving the wire to the left. This can be confusing because when the magnet is moved to the right, even through the wire is stationary, the wire is actually moving to the left with respect to the magnetic flux.

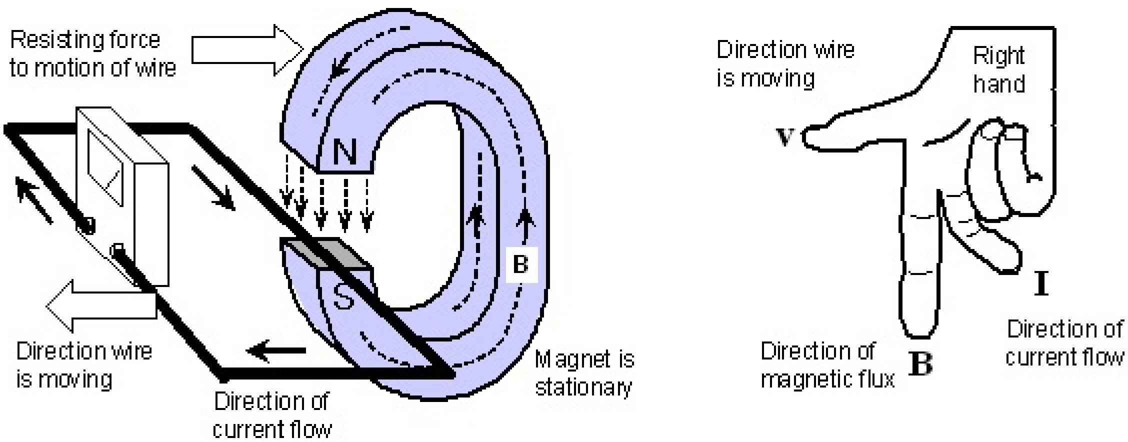

Figure 217.8 *If a wire forming a circuit is moved through a magnetic flux, a current will flow in the wire. The right hand rule can be used to determine the direction of current flow in the wire knowing the direction of magnetic flux and direction the wire is moving with respect to the magnetic flux.*

Mutual Induction: *If an ac current is applied to a coil of wire, the alternating current creates an alternating magnetic field.* The magnetic flux around the coil builds up with the North pole at one end of the coil and the South pole at the other end. Then the current stops, reverses direction, and then flows in the opposite direction. This causes the magnetic poles to reverse as illustrated in *Figure 217.9. With alternating current applied to the coil of wire the magnetic flux is constantly moving* even though the coil of wire is stationary.

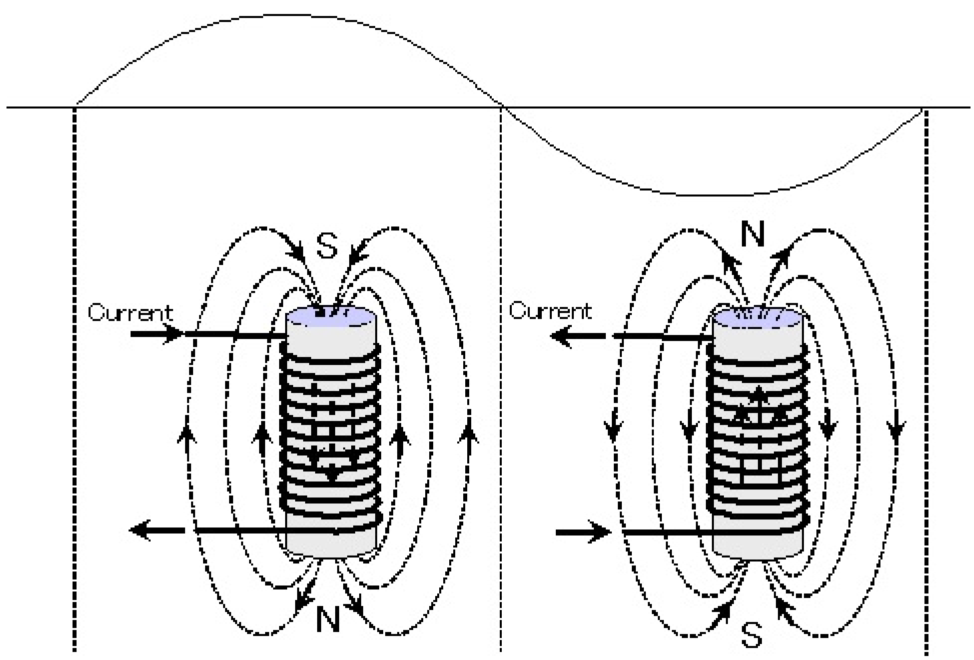

Figure 217.9 *The magnetic flux about a coil of wire is in constant motion when alternating current is applied to the coil with the magnetic poles constantly reversing.*

If a second coil of wire is placed next to the first coil the moving magnetic flux caused by the alternating current flow through the first coil will cut across the wires of the second coil. A current flow will be induced into the second coil if it forms a complete circuit. By ***mutual induction***, *a current is induced into the second coil circuit by the current flow through the first coil.* This is the principle of operation of a transformer. A transformer is illustrated in *Figure 217.10.* The voltage produced in the second coil is equal to the voltage applied to the first coil times the ratio of the number of turns of wire on the second coil divided by the number of turns of wire on the first coil. Note that the two coils are electrically independent of each other and linked only by the magnetic flux. A transformer is useful for isolating one circuit from another. Because the voltage applied to the first coil as compared to the second coil is dependant upon the number of turns of wire on both coils. A transformer can be used to change voltage level in a circuit.

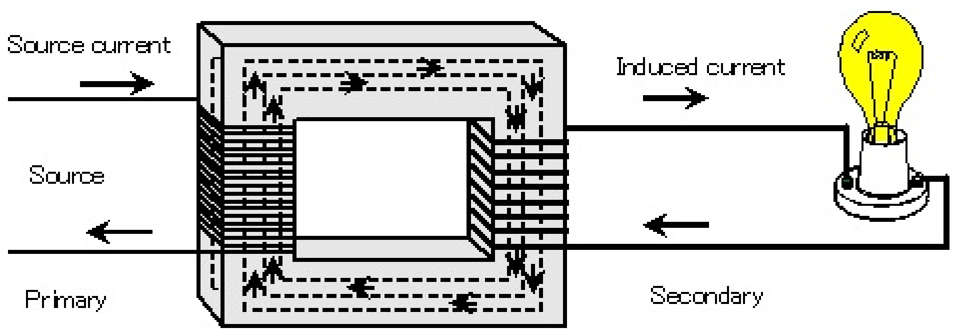

Figure 217.10 *By mutual induction, the current flow in the primary winding of a transformer induces current to flow in the secondary circuit. The ratio of number of primary coils to secondary coils determines the ratio of secondary circuit voltage compared to the primary circuit voltage.*

Self Induction: If a voltage can be induced into a wire that is placed in a moving magnetic flux, then by a process called *mutual induction,* one wire in a coil will have a magnetic effect upon an adjacent wire in the coil. Note in *Figure 217.11* the magnetic flux of one wire cuts across the adjacent conductors and induces a reverse voltage in adjacent wires of the coil. This is referred to as a reverse voltage or reverse *emf*. The level of the reverse voltage is dependant upon the current flow through the coil. The process that produces this reverse voltage is called ***self induction***. Self induction is a phenomenon of a coil energized with alternating current and produces an opposition to current flow in addition to the resistance of the wire in the coil.

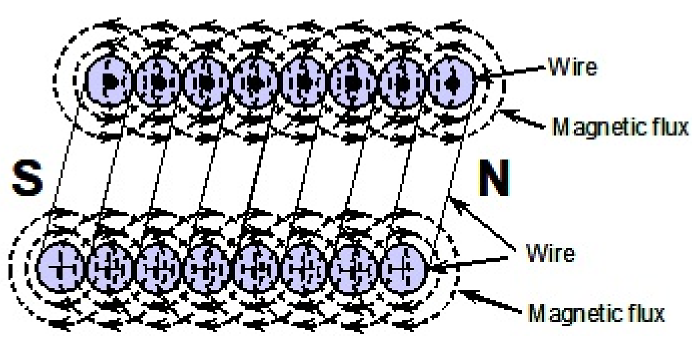

Figure 217.11 *By self induction the current flow in one wire of a coil will induce a reverse voltage in adjacent wires that will oppose the flow of current in the coil. Along with wire resistance self induction helps limit current flow in the coil to a maximum level.*

Direction of Current Flow in Wires: The magnetic field all along an electrical wire encircles the wire in a particular direction depending on the direction of current flow. If a person could view a wire cross section and determine direction of current flow than orientation of the magnetic field can be determined.

A "**dot**" in the middle of the wire cross section indicates the current is flowing towards the observer. If a "**plus sign**" is observed then the current is flowing away from the observer. This is illustrated in *Figure 217.12.* This is important to remember because knowing the direction of current flow through a wire is necessary to determine the orientation of the magnetic field around the wire. Understanding orientation of the magnetic field is essential to understanding how electrical equipment operates. Using the thumb of the right hand, point the thumb in the direction the current is flowing.

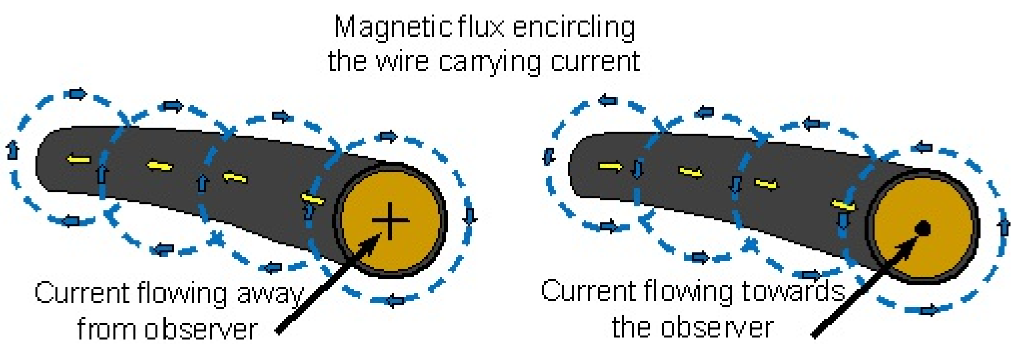

Figure 217.12 *Viewing the wire cross section with current flowing towards the observer (right diagram) the magnetic field encircles the wire in the counter-clockwise direction.*