CONSTRUCTION ELECTRICIAN APPRENTICESHIP PROGRAM

Level 1 — Line D: Apply Circuit Concepts



LEARNING GUIDE D-3

SOLVE PROBLEMS USING THE PRINCIPLES OF MAGNETISM

ita
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THE RIGHT SKILLS ▶ A PROVEN ADVANTAGE

BRITISH COLUMBIA

Foreword

The Industry Training Authority (ITA) is pleased to release this major update of learning resources to support the delivery of the BC Electrician Apprenticeship Program. It was made possible by the dedicated efforts of the Electrical Articulation Committee of BC (EAC).

The EAC is a working group of electrical instructors from institutions across the province and is one of the key stakeholder groups that supports and strengthens industry training in BC. It was the driving force behind the update of the Electrician Apprenticeship Program Learning Guides, supplying the specialized expertise required to incorporate technological, procedural and industry-driven changes. The EAC plays an important role in the province's post-secondary public institutions. As discipline specialists the committee's members share information and engage in discussions of curriculum matters, particularly those affecting student mobility.

ITA would also like to acknowledge the Construction Industry Training Organization (CITO) which provides direction for improving industry training in the construction sector. CITO is responsible for organizing industry and instructor representatives within BC to consult and provide changes related to the BC Construction Electrician Training Program.

We are grateful to EAC for their contributions to the ongoing development of BC Construction Electrician Training Program Learning Guides (materials whose ownership and copyright are maintained by the Province of British Columbia through ITA).

Industry Training Authority
January 2011

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LEVEL 1, LEARNING GUIDE D-3:

SOLVE PROBLEMS USING THE PRINCIPLES OF MAGNETISM

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Learning Objectives

- The learner will be able to describe the principles of electromagnetism.
- The learner will be able to solve problems involving magnetic circuits.

Activities

- Read and study the topics of Learning Guide D-3: Solve Problems Using the Principles of Magnetism.
- Complete Self-Tests 1 to 4. Check your answers with the Answer Key provided at the end of this Learning Guide.

Resources

You are encouraged to obtain the following texts to provide supplemental learning information:

Direct Current Fundamentals by Orla E. Loper and Edgar Tedsen; Eighth edition;
Delmar Publishers Inc.

Electrical Systems Technology Circuits Motors Generators Controls by Walter L. Bartkiw and Kenny T. Soakloo; McGraw-Hill Ryerson Ltd.,1986

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Industry Training Authority
January 2011

Learning Task 1:

Describe the characteristics of magnetic lines of force

Magnetic field

All magnets have two points opposite each other where the field force is strongest: two points where the magnetic flux is most dense. These points are referred to as the *magnetic poles*. They are the points at which the magnetic lines of force enter and leave the magnet. It is not possible to have one pole without having the other.

A *magnetic field* is the region in which a magnetic material is acted upon by a magnetic force. You can think of it as being made up of invisible lines of force. These lines of force represent the path along which a theoretical isolated magnetic pole would travel from one pole of the magnet to the other pole of the magnet.

A good representation of these magnetic lines can be seen by placing a bar magnet beneath a piece of paper, and then sprinkling iron filings over the paper. The iron filings align themselves as shown in Figure 1. Notice how the filings are more concentrated at the two poles on the left and right. These poles are labelled S and N, for south and north.

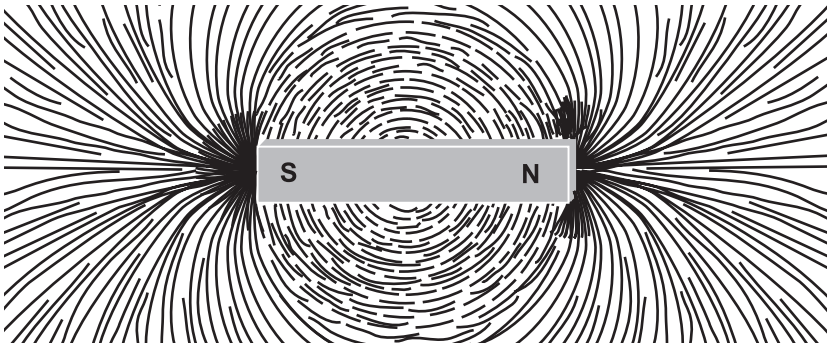


Figure 1—Lines of force of a magnet

If a magnet is suspended on a string, one end always points to the north pole of the Earth. This pole of the magnet is referred to as the *north pole*. The other end of the magnet is referred to as the *south pole*. This implies that the north geographic pole of the Earth is actually a south magnetic pole (remember that unlike poles attract). This confusion arises because early users of compasses labelled one compass pole as the *north-seeking pole*, meaning that it pointed roughly toward the geographic North Pole.

Characteristics of magnetic lines of force

- *Magnetic lines of force possess direction*.

The way to observe this is by following the path of a flux line with a compass. The compass needle always aligns itself with the flux lines, and the north pole of the compass always points toward the south pole of the magnet. See Figure 2.

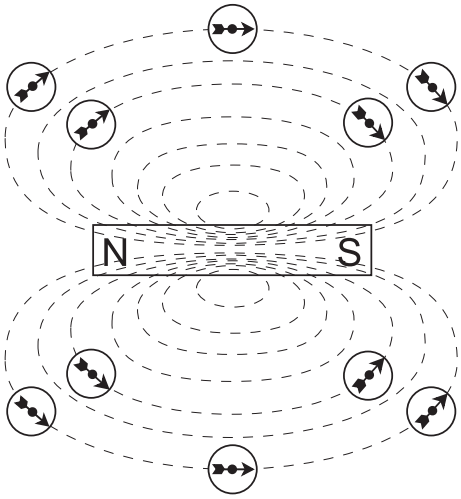


Figure 2—Direction of magnetic lines of force

Magnetic lines of force are considered to flow out of the north pole and into the south pole. This direction is normally shown using arrows (Figure 3).

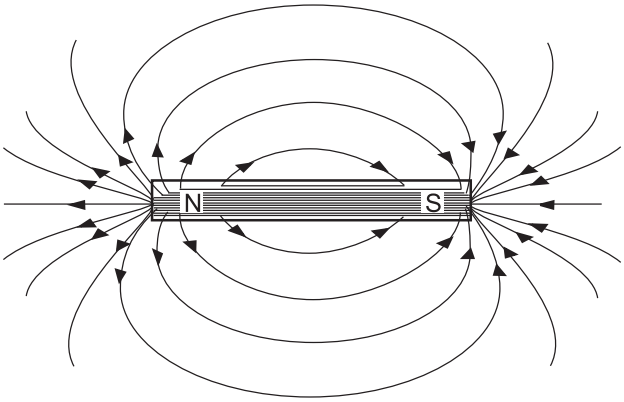


Figure 3—Magnetic lines flowing from north to south

- *Magnetic lines of force always form complete loops.*

  They do not begin at the north pole and end at the south pole, but continue through the magnet to form complete loops as shown in Figure 4a. The easiest way to see this is by cutting a magnet into smaller pieces and observing the presence of the magnetic field between the pieces of the magnet. See Figure 4b.

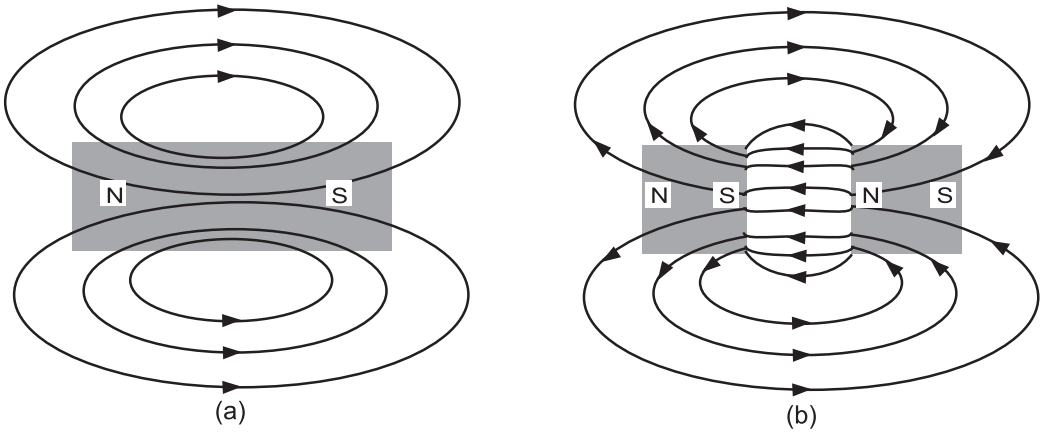


Figure 4—Magnetic loops

- *Magnetic lines of force represent tension along their length that tends to make them as short as possible.*

  This means they act like elastic bands trying to collapse inward. If you cut a magnet in two and try to pull the pieces apart, it is as though you are stretching the magnetic lines of force. They will try to pull back together to reduce the length of the magnetic lines of force. This accounts for the fact that unlike poles of magnets attract one another. Rather than forming two loops, the total length of the magnetic flux lines become shorter if they form one big loop and pull together (Figure 5).

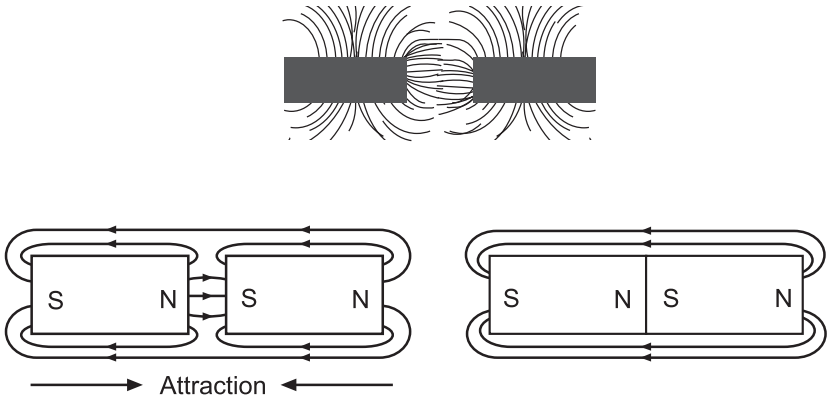


Figure 5—Magnetic tension

- *Magnetic lines of force repel each other.*

  If magnetic lines of force act like elastic bands, why don't they collapse into the centre? The reason is that they repel each other. Notice that they tend to diverge as they move away from the poles, rather than converge or even remain parallel (Figure 6). This results from their mutual repulsion.

- *Magnetic lines of force cannot intersect or cross, but must always form individual loops.*

  The mutual repulsion accounts for this effect. This also accounts for the fact that like poles of magnets repel each other. See Figure 6.

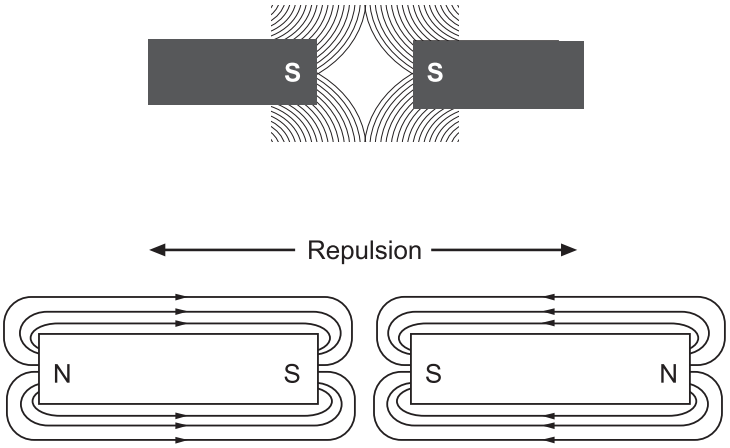


Figure 6—Like poles repel

- *Magnetic lines of force always tend to arrange themselves in such a manner that the maximum number of lines of force are set up.*

  Because iron makes it easier to increase the lines of force in a given area, the magnetic lines of force will distort to include a piece of iron in the field. This will have the effect of turning the iron into a temporary magnet. Then the opposite poles of the two magnets will attract each other and try to shorten the flux lines. This accounts for the attraction of unmagnetized ferromagnetic objects to the closer pole (Figure 7).

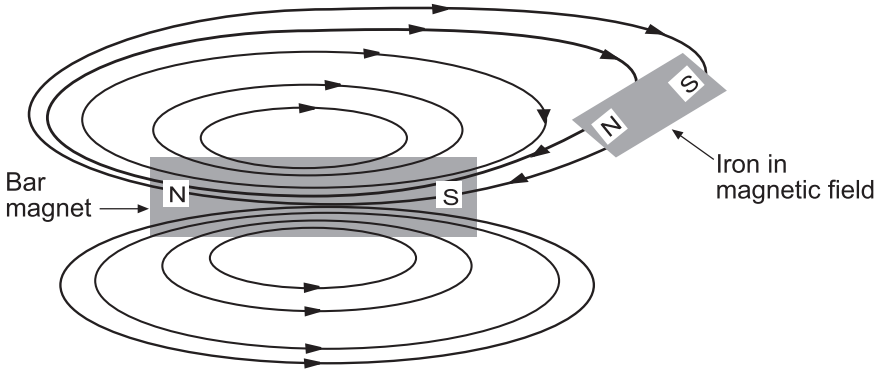


Figure 7—Ferromagnetic object attracted to closest magnetic pole

Magnetic screens

Some objects and equipment are adversely affected by magnetic fields. For example, a magnetic field too close to a colour television will cause the colour in the picture to distort. Another example is that clocks and watches may not keep proper time when exposed to magnetic fields.

For this reason, some objects must be protected from the effects of magnetic lines of force. Because magnetic lines of force can flow through any material, you cannot block the lines of force. What you do instead is deflect the lines of force *around* the object you are trying to protect.

Reluctance

Flux lines pass through some materials more easily than others. The property that *opposes* the setting up of flux lines is known as *reluctance*. Materials with a low reluctance tend to concentrate Magnetic flux. Given a choice, most lines of force in a magnetic field will pass through low, reluctance material.

Soft iron has a reluctance that is much lower than that of air. If the flux has a choice of setting up in air or in iron, the lines will concentrate in the iron. You build a magnetic screen of iron by surrounding the item you wish to protect with iron. This deflects the lines of force around the item, protecting it from the adverse effects of magnetism.

Using this principle, you can construct a path that causes flux to divert around something that you are trying to shield from magnetic lines of force. This type of device is called a *magnetic screen*. See Figure 8.

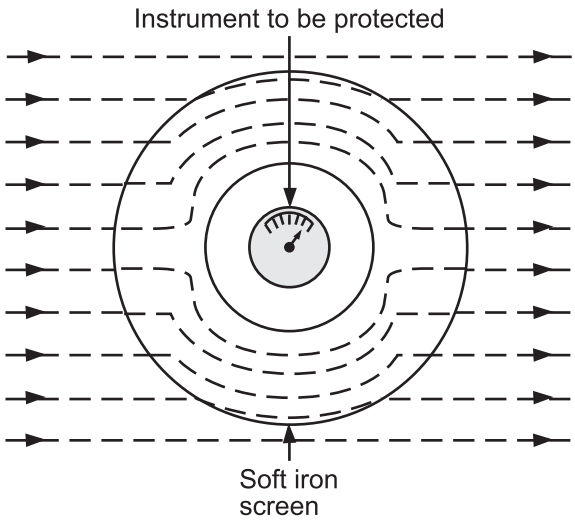


Figure 8—Magnetic screen

Magnetism by induction

As stated previously, magnetic lines of force always tend to arrange themselves in such a manner that the maximum number of lines of force are set up. For this reason, if a piece of ferromagnetic material is brought near a magnet, the lines of force arrange themselves so that they include the piece of ferromagnetic material in their path. This can be seen in Figure 9.

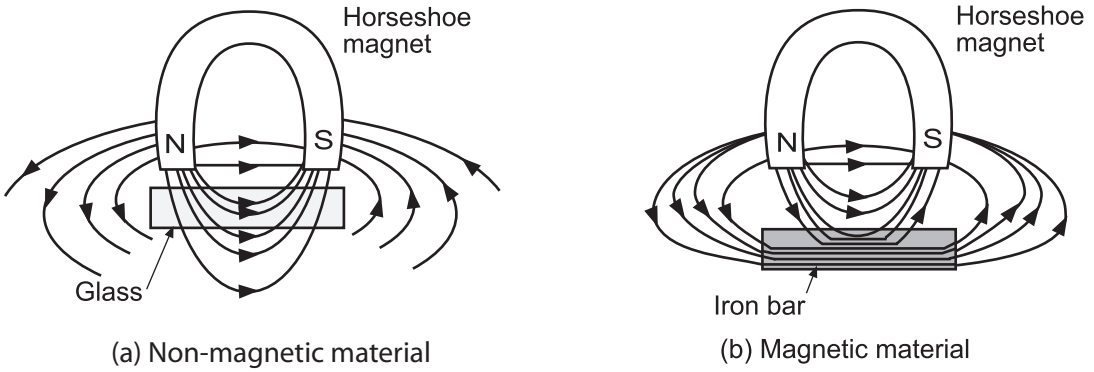


Figure 9—Magnetism by induction

The magnetic lines of force tend to align and concentrate within the ferromagnetic material. This causes poles to be established at the points where the lines of force enter and leave the ferromagnetic material. This process is referred to as *magnetism by induction*.

If the ferromagnetic material is:

- soft iron (iron with a low carbon content), the iron is easily magnetized. But it loses its magnetism as the magnetic field is removed.
- hard iron or steel (with a high carbon content), it requires a much stronger magnetic field to be magnetized. However, when the magnetic field is removed, the iron material retains most of its magnetism.

Common methods of producing artificial magnets

Ferromagnetic material can be magnetized in several ways.

Using electric current

The most effective way is by using an electric current. Remember that anytime a current flows in a conductor, a magnetic field is set up around the conductor. To increase the strength of this magnetic field, wind the conductor into a coil. The magnetic flux lines add to each other and produce a much denser magnetic field in the centre of the coil.

A north pole is created at one end of the coil and a south pole is created at the other.

Which end is north and which end is south depends upon the direction the current travels through the conductor.

If a piece of ferromagnetic material is placed in the coil and a current is passed through the coil in one direction, the magnetic field of the coil causes the domains to align in the ferromagnetic material. This causes poles to form in the ferromagnetic material, and creates an electromagnet as shown in Figure 10.

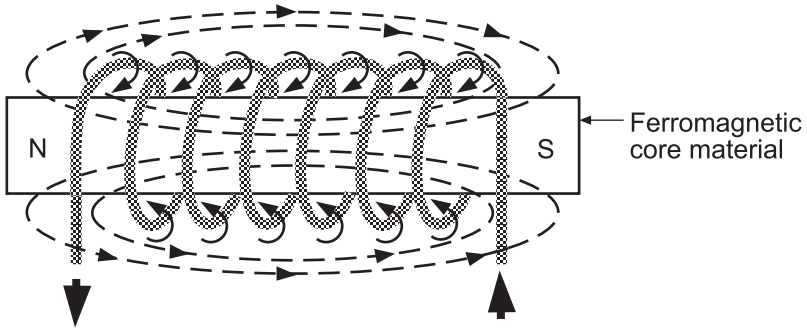


Figure 10—Electromagnet

Stroking with a magnet

Another method of producing a magnet is by stroking a piece of ferromagnetic material with a magnet (Figure 11). The field of the stroking magnet aligns the domains in the ferromagnetic material, causing it to become magnetized.

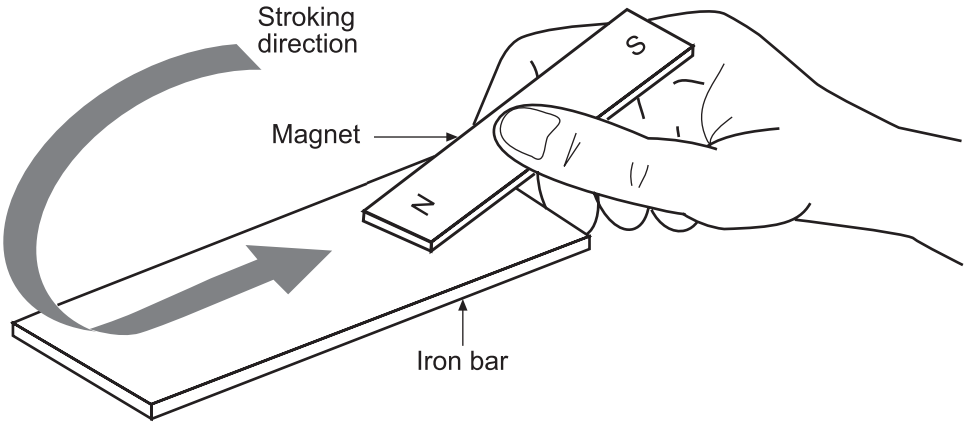


Figure 11—Magnetizing a ferromagnetic material by stroking with a magnet

Aligning with a magnetic field and tapping

A third, less effective way to produce a magnet is to align a piece of ferromagnetic material with any magnetic field, even that of the Earth, and tap it lightly. The tapping produces enough energy to align some of the domains with the magnetic field, causing the ferromagnetic material to become magnetized.

Common methods of demagnetizing ferromagnetic materials

There are also several methods for removing magnetism from ferromagnetic materials.

Using electric current

Just as an electric current passing through a coiled conductor can be used to magnetize a piece of ferromagnetic material, it can also be used to demagnetize the material.

When magnetizing the material, the current is passed in one direction only. When demagnetizing a piece of ferromagnetic material, you use a source of current that changes direction constantly and rapidly. This type of current is called an *alternating current*. This alternating current causes the north and south poles of the coil to switch poles back and forth very quickly. This causes the poles in the ferromagnetic material to change back and forth, and causes the domains to flip back and forth as well.

If you either slowly remove the material from the coil or slowly reduce the current in the coil, then the field becomes weaker and the domains will be left in a random orientation within the material. Because of this random orientation, the ferromagnetic material will no longer be magnetized. This is the method that watchmakers often use to demagnetize watches.

Using heat

A very effective method of demagnetization is to apply heat to the magnet. At a certain temperature, called the *Curie temperature*, the molecular structure of the ferromagnetic material rearranges itself and the alignment of the domains is lost even after the material is cooled. Each substance has a different Curie temperature, but for iron it is about 770°C. That is the point at which the iron starts to glow a cherry red.

Using vibration

A third way of removing magnetism is by tapping or vibrating the magnet. As the material is magnetized, the domains are moved and the bonds are stressed. When the magnet is vibrated, energy is supplied and the stress tends to restore the domains to their original orientation. The magnetism is lost.

Precautions to observe to avoid damaging magnets

Avoid subjecting magnets to conditions that demagnetize them. This means:

- Do not expose magnets to heat.
- Do not place magnets near fields created by alternating currents.
- Do not drop magnets or subject them to excessive vibration.
- Do not store magnets near other magnets.

Keepers

Many types of magnets are stored with a device called a *keeper*. This is usually a piece of soft iron placed across the poles of the magnet to provide an easy path for the magnetic flux (Figure 12). If it is not used, the magnetic field will weaken over time.

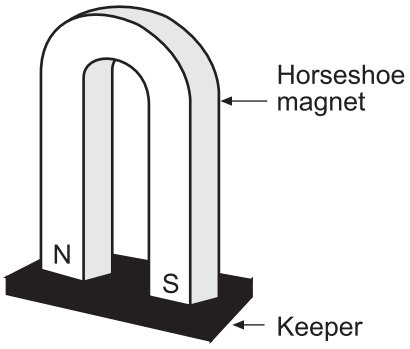


Figure 12—Proper storage of a magnet

Now do Self-Test 1 and check your answers.

Self-Test 1

1. What is another name for magnetic lines of force?

   _____

2. Why don't magnetic lines of force collapse into the centre of a magnet?

   _____

3. Magnetic lines of force never cross.
   a. True
   b. False _____

4. Magnetic lines of force start at the north pole and end at the south pole.
   a. True
   b. False _____

5. It is not possible to have a north pole without having an accompanying south pole.
   a. True
   b. False _____

6. The north pole of the Earth is actually a south magnetic pole.
   a. True
   b. False _____

7. The arrows on the magnetic lines of force always point from north to south outside of the magnet, and south to north on the inside of the magnet.
   a. True
   b. False _____

8. Unlike poles of magnets repel each other.
   a. True
   b. False _____

9. Magnetic screens are made of material with a low reluctance.
   a. True
   b. False _____

10. Magnetic screens block magnetic flux lines.
    a. True
    b. False _____

11. List three ways of creating magnets.

    _____

    _____

    _____

12. List three ways of demagnetizing a material.

    _____

    _____

    _____

13. Which method of demagnetizing is commonly used by watchmakers?

    _____

14. What is meant by the term *Curie temperature*?

    _____

15. When a piece of ferromagnetic material is brought near a magnet, the ferromagnetic material becomes magnetized. This process is referred to as _____ .

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 2:

Describe the effects of current-carrying conductors and coils

In about 1826 a Danish physicist named Hans Christian Oersted noticed that a compass placed near a conductor reacted anytime a current flowed in the conductor. From this and other experiments, it was concluded that electricity and magnetism were related.

We now know that the moving charges and magnetic fields are inseparable. One cannot exist without the other. Since a current flowing in a conductor is made up of moving charges, it follows that anytime a current flows through a conductor, a magnetic field is created around that conductor.

It is possible to explore the magnetic field around a conductor by using small compasses or iron filings. Figure 1 shows the lines of force that form in concentric circles around a conductor.

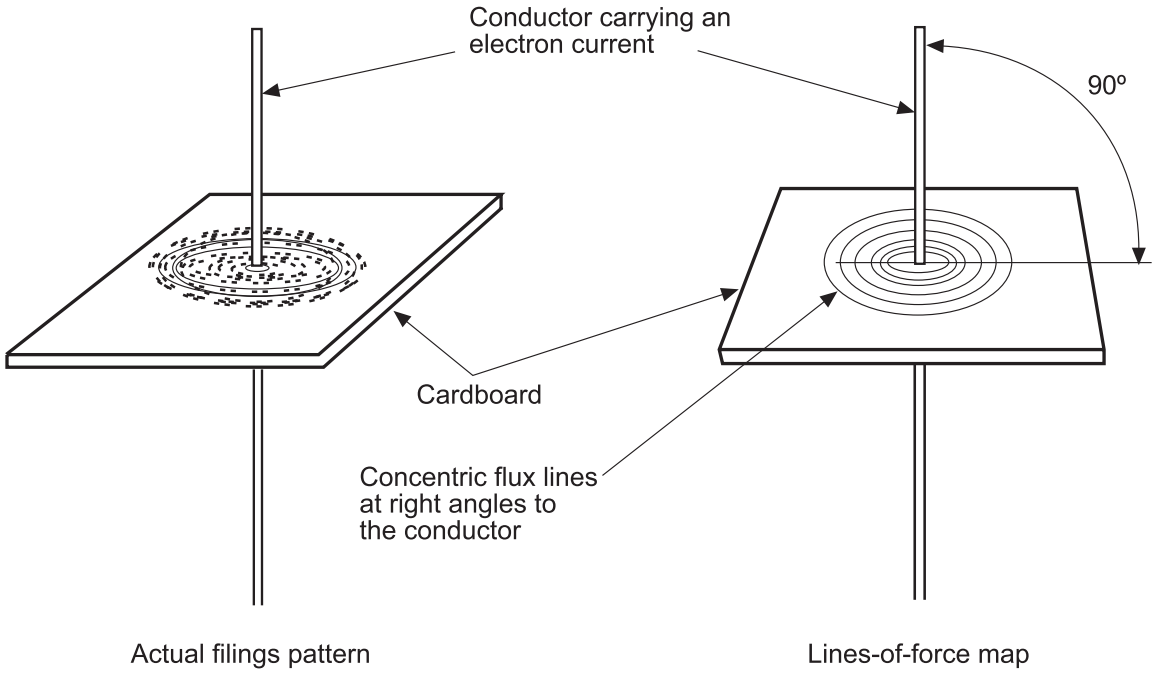


Figure 1—Magnetic field around a current-carrying conductor

As current starts to flow in the conductor, loops of magnetic lines of force form at the centre of the conductor. As current increases, more loops form at the centre of the conductor. Because these lines of force repel each other, the new loops forming at the centre force existing loops outward. This works much the same way as when a rock is dropped into a pond. The rings of waves form at the point where the rock is dropped and the new waves push the existing waves outward. Flux loops continue to expand outward for as long as the current continues to increase. Because of the elastic nature of the flux lines, the outer loops apply a squeezing force on the inner loops. Therefore, loops near the centre are spaced closer together than those further out.

The magnetic field is stronger near the conductor than it is further away. The number of lines of force per unit area is inversely proportional to the distance from the conductor. For example, the number of lines of force per unit area (field density) 1 metre from the conductor is one half of what it is 0.5 metre from the conductor.

If the current in the conductor is constant, the flux loops remain stationary. If the current decreases, the flux lines collapse inward. When the current stops, all the flux lines collapse into the centre and disappear. Note that these loops of magnetic flux lines act in a plane (flat surface) at right angles to the conductor.

There are no points where these lines of force diverge or converge, so there are no magnetic poles formed around the current-carrying conductor. However, by placing small compasses around the conductor, it is possible to show that these flux lines do possess direction. If the direction of current through the conductor is reversed, the compasses around the conductor all reverse direction at the same time. See Figure 2.

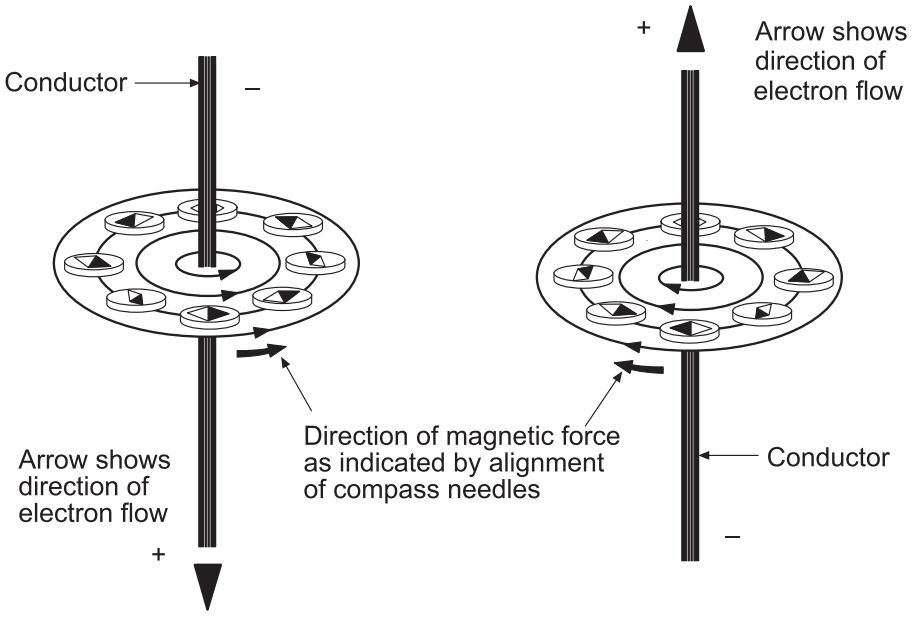


Figure 2—Direction of flux lines

The left-hand rule can be used to determine the direction of flux lines around the current-carrying conductor. See Figure 3. Imagine your left hand to be wrapped around the conductor so your thumb points in the direction of electron flow. Your fingers then wrap around the conductor in the direction of the flux lines.

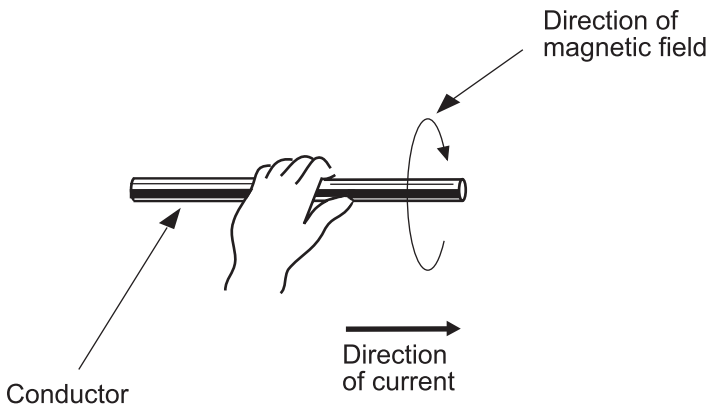


Figure 3—Left-hand rule

A dot-and-cross convention is used to indicate the direction of current flow in conductors entering or leaving the page. See Figure 4.

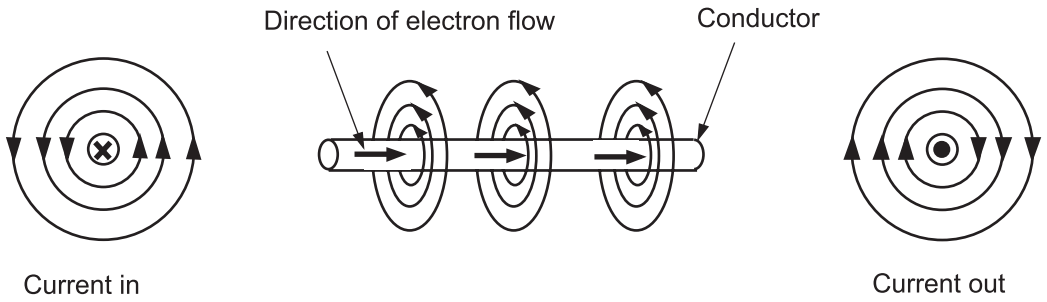


Figure 4—Symbols representing current direction

The dot and cross represent the ends of an arrow. The dot is the tip of the arrow as seen coming toward you. It is used to indicate a current leaving the page, travelling toward you. The cross is the feather of the arrow as seen moving away from you. It indicates a current entering the page, travelling away from you.

Magnetic force

If two current-carrying conductors are placed parallel to each other, they exert a force on each other. The direction of the force will depend on the direction of current flow in one conductor with respect to the other.

Figure 5 illustrates two conductors carrying currents in the same direction. The flux lines around the conductors form into one single loop, trying to become as short as possible. This causes the two conductors to attract each other.

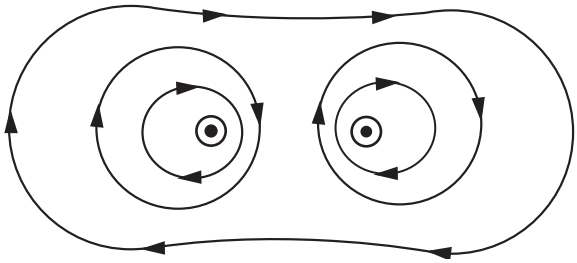


Figure 5—Same-direction currents attract

Figure 6 illustrates two parallel conductors carrying currents in opposite directions. Because the flux lines around the conductors are in opposite directions, they cannot join into one loop. Flux lines can never cross, so they become crowded into the space between the conductors.

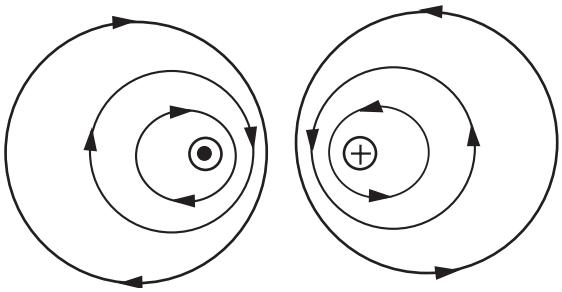


Figure 6—Opposite currents repel

Another property of flux lines is that they repel each other. For this reason, the flux lines crowded between the two conductors try to repel each other, and this results in a force of repulsion between the two conductors.

Stated in simple terms, parallel conductors carrying currents in the same direction attract each other and conductors carrying currents in opposite directions repel each other.

Magnitude

The magnitude of the force between parallel conductors is directly proportional to the product of the currents flowing in the conductors and inversely proportional to the distance between the conductors. This can be expressed in the following equation:

$$F_m = \frac{k \times I_1 \times I_2}{d^2}$$

Where:

F is the force in newtons.

I_1 is the current in the first conductor.

I_2 is the current in the second conductor.

d is the distance between the conductors in metres.

k is a constant for the medium between the conductors.

When short circuits occur, the currents in both conductors may reach levels in the hundreds of thousands of amperes before the overcurrent device opens the circuit. Tremendous forces may act on the conductors during this time. If the conductors are not properly braced, extreme physical damage can occur. Engineers calculate the forces that might occur during short circuits and design busbars and bracing to withstand them.

Conductors wound into coils

A stronger magnetic field may be created by winding conductors into a coil as in Figure 7.

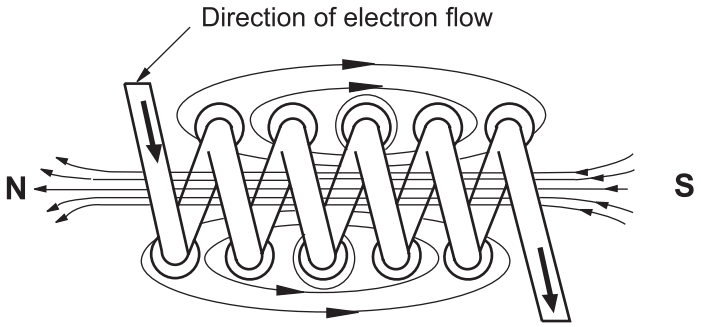


Figure 7—Magnetic flux in a loop

Because the loops of the coil are wound in the same direction, the effects of the individual loops are added together. The majority of the flux lines are in the centre of the coil. These flux lines are forced together in a concentrated area, which increases the flux density and strengthens the magnetic field.

As the flux lines enter the coil they converge (move closer together) and as they leave the coil they diverge. These points of convergence and divergence cause poles to form at the ends of the coil. The existence of these poles can be confirmed by using compasses. The flux lines leave the coil at the north end and enter the coil at the south end.

Such a spiral-shaped coil is called a *helix*, and the coil is said to be *helically wound*. A helically wound coil that produces a strong magnetic field is referred to as a *solenoid*.

Left-hand rule for coils

To determine which end of the coil is the north pole and which is the south pole, use the left-hand rule for coils. Wrap the fingers of your left hand around the coil so that your fingers point in the direction of the electron flow (current). Then your left thumb points in the direction of the north pole. See Figure 8.

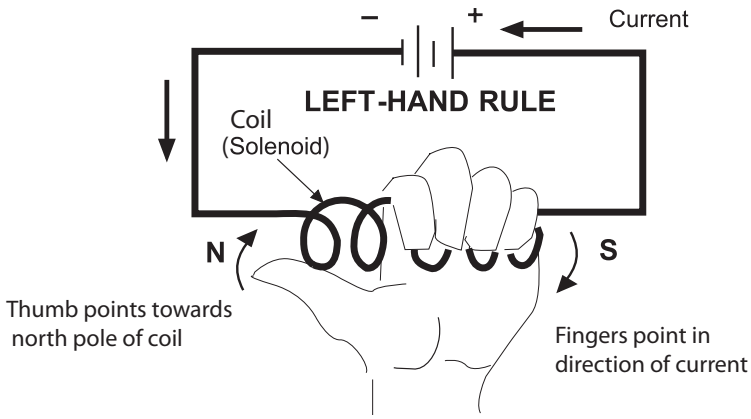


Figure 8—Left-hand rule for a coil

By using a compass and the left-hand rule, it is possible to determine the direction of current flow in the coil. First use the compass to locate the north pole of the coil. Then grasp the coil so that the thumb of your left hand points in the direction of the north pole. The fingers of your left hand will point in the direction of electron flow.

Factors affecting the strength of an electromagnet

Several factors affect the strength of an electromagnetic coil. These are:

- the spacing between coils for an air-core electromagnet
- the number of turns in the coil
- the magnitude of the current flowing through the coil
- the type of material from which the core is made

If the loops of the coil are wound closer together, more of the flux lines are forced into the centre of the coil, increasing the flux density and strengthening the field. As the flux density is decreased, so is the strength. See Figure 9.

As more loops are added to the coil, the fields combine to make the flux lines through the coil more dense, increasing the strength of the magnetic field.

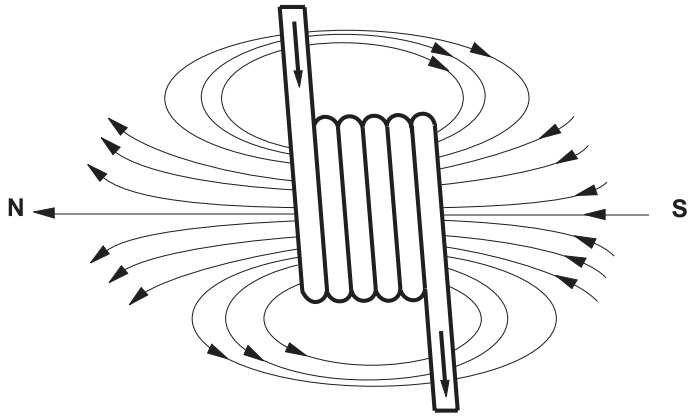


Figure 9—Close-wound coil with high flux density

Some of the lines of force leave and enter the coil before reaching the ends of the coil. This is referred to as *leakage flux*. The number of lines of force that do this increases as the length of the coil increases. When this happens, the flux density of the coil is far less at the ends of the coil than in the centre. Also, the flux lines are more spread out at the ends of the coil, as can be seen in Figure 9.

As the current through the coil is increased, the number of flux lines surrounding the conductor loops is increased, causing more lines to be created inside the coil. This increases the flux density, further strengthening the field.

Some materials permit the setting up of flux lines more easily than others. If these types of materials are placed inside the coil, the flux density increases, strengthening the field. These types of materials are known as *ferromagnetic materials*, because they act similarly to iron when placed in a magnetic field.

If a non-magnetic material such as wood or aluminum is placed in the coil, it has little or no affect on the strength of the field within the coil. It does not aid in the setting up of flux lines and therefore does not increase the flux density.

The most practical way to vary the strength of an electromagnet is to vary the current through the coil. It is far easier to do this than to change the number of turns in the coil or change the core material. Practical electromagnets used for such things as lifting devices, motors, and generators often have their coils connected in series with a rheostat (variable resistor), which can be used to vary the current through the coil. This changes the flux density and the strength of the magnet.

 Now do Self-Test 2 and check your answers.

Self-Test 2

1. Is it true that any time a charge moves, there must be a magnetic field set up around that charge?

2. Why are there no magnetic poles in the field surrounding a current-carrying conductor?

3. As the direction of current in a conductor is reversed, what happens to compasses surrounding the conductor?

4. What does the action in Question 3 indicate?

5. As the current in a conductor is increased, what happens to the magnetic lines of force surrounding the conductor?

6. When the current remains steady, does the field disappear?

7. Is the field around the conductor more dense or less dense closer to the conductor?

_____

8. What causes the effect in Question 7?

_____

_____

_____

9. As the current in a conductor is decreased, what happens to the magnetic lines of force surrounding the conductor?

_____

_____

_____

10. In moving four times as far away from a current-carrying conductor, the density of the flux lines will have _____ by _____ times.

11. Parallel conductors carrying currents in the same direction _____ each other and parallel conductors carrying currents in opposite directions _____ each other.

12. Using the left-hand rule for coils, the thumb points in the direction of

_____.

13. List four things that affect the strength of an electromagnetic coil.

_____

_____

_____

_____

14. Materials that act in a similar way to iron in a magnetic field are referred to as _____ materials.

15. Give two examples of non-magnetic materials.

_____

_____

16. What is the most practical way of varying the strength of an electromagnet?

_____

_____

_____

17. What device connected in series with the electromagnet is normally used to do this?

_____

_____

_____

18. As you move two times the distance away from a conductor, the flux density of the field will decrease by _____ times.

19. Why must electrical busbars be securely braced?

_____

_____

20. In the dot-and-cross convention used to indicate the direction of current flow, a _____ represents a current coming out of the page toward you.

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 3:

Describe the terminology and units of measure for magnetic circuits

An understanding of the terminology of magnetic circuits is critical to understanding the operation of these circuits. It is also required for communicating that understanding to others in the field. The terminology used in the study of magnetism very closely parallels the terminology used in electric circuits.

Magnetic circuit refers to the path along which the flux lines follow as they form their complete loops. There is a basic law for magnetic circuits that is similar to Ohm's law in electric circuits. It can be stated as follows:

> *The magnetic flux in a circuit is directly proportional to the magnetomotive force and inversely proportional to the reluctance of the magnetic circuit.*

This can be expressed as the following equation:

$$\Phi = \frac{F_m}{R_m}$$

Magnetic flux is the total number of flux lines in a magnetic circuit. It is the counterpart of current in an electric circuit. There is one very important difference to keep in mind: flux lines do not flow. The symbol for the quantity of flux is the Greek letter Phi (Φ). The unit of magnetic flux is the weber, equal to 10^8 flux lines. Its abbreviation is Wb.

Magnetomotive force is the force that causes the setting up of flux lines in a magnetic circuit. It is the counterpart of electromotive force in an electric circuit. The magnetomotive force (mmf) in a magnetic circuit is equal to the number of coil turns in the circuit times the current through those coils. The symbol for the quantity of magnetomotive force is F_m. The unit of mmf is the ampere-turn. Its abbreviation is A. t.

Reluctance is the opposition to the setting up of flux lines in a magnetic circuit. It is the counterpart of resistance in an electric circuit. The reluctance of a magnetic circuit is equal to the mmf divided by the flux. The symbol for the quantity of reluctance is R_m. The unit of reluctance is the ampere-turn per weber. Its abbreviation is A•t/Wb.

The reluctance in a magnetic circuit increases as the length of the circuit increases and decreases as the cross-sectional area of the circuit increases. (Just as resistance does.) The reluctance of a circuit also depends on the type of material used in the core of the circuit. (Just as resistance does.)

There are other magnetic quantities with parallels in electricity. The columns on the next page describe them.

Electrical term	Magnetic term
Current density In an electric conductor it is possible to refer to the amount of current flowing per unit cross-section of the conductor. This is referred to as the *current density*.	*Flux density* is the measure of the amount of flux per unit cross-section of the magnetic circuit. The symbol for the quantity of flux density is the Greek letter beta (β). The unit of flux density is the tesla, which equals webers per square metre. The abbreviation for tesla is T.
Voltage gradient is the measure of electromotive force per unit length in an electric circuit or field. It is a measure of the voltage between two points divided by the distance between the same two points.	*Magnetizing force* (also referred to as magnetizing intensity or magnetizing gradient) is the measure of the magnetomotive force per unit length in a magnetic circuit. The symbol for the quantity of magnetizing force is the letter H. The unit of magnetizing force is the ampere-turn per metre. The abbreviation for ampere-turn per metre is A•t/m.
Resistivity in an electric circuit is the resistance of a unit length and cross-section of a certain material. Conductivity is the reciprocal relationship. It is the ease with which current may be passed through a unit length and cross-section of a certain material. It is a measure of the current density per voltage gradient.	*Permeability* is the measure of the ease with which flux may be set up in a unit length and cross section of a material. It is a measure of the flux density per magnetizing force. The symbol for permeability is the Greek letter mu (μ). The unit of permeability is the weber per ampere turn metre or henries per metre, abbreviated to Wb/A.t.m or H/m. The permeability of free space (air) is $4\pi \times 10^{-7}$ Wb/A.t.m.

Magnetization curves

The permeability of most materials is not constant. Except at very low levels of flux density, the permeability of most magnetic materials decreases as the flux density increases. This works much the same way as stuffing toothpicks into a container. The first ones go in very easily, but as the container fills it becomes harder and harder to squeeze in the next one. As more and more flux lines are set up in a magnetic material, the ease with which the next ones are set up decreases.

The permeabilities of different ferromagnetic materials cannot be expressed as a single number because the value depends upon the flux density in the material.

Instead, graphs of flux density with respect to magnetizing intensity are plotted for a magnetic material. The resulting curve is the *magnetization curve* of a material. It is also called a *B-H graph* or curve. Figure 1 contains the B-H curves for several ferromagnetic materials.

The permeability of a material at a given flux density is determined from the slope of the curve.

The B-H graph for air would be a straight line almost parallel to the × axis and almost touching it. Non-magnetic materials such as aluminum and plastic would have curves very close to that of air.

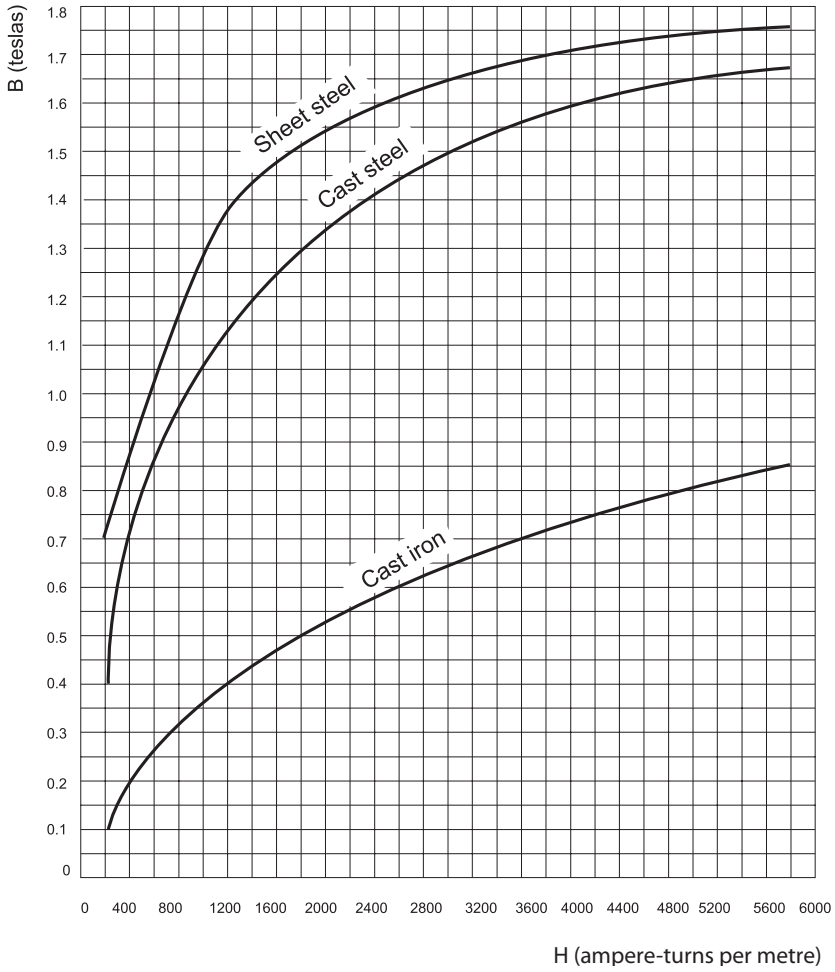


Figure 1—B-H graph

Notice that the curves tend to level out. At some point when all of the domains in the magnetic material have been aligned with the magnetic field, the gain in flux density for a given increase in magnetizing force is no more than would occur in air for the same increase. At this point the magnetic material is said to be *saturated*. (What the curves do is approach the slope of the magnetization curve for free space.)

Theoretical saturation occurs at the point where all of the domains in the magnetic material have aligned themselves with the magnetic field.

Practical saturation occurs when it is no longer practical to try to increase the flux density. That is, the gain in flux density for an increase in magnetizing force is so small that it is not worth it. This occurs at a point on the curve called the *knee*. This is the point where the curve takes a sharp bend to level off (Figure 2).

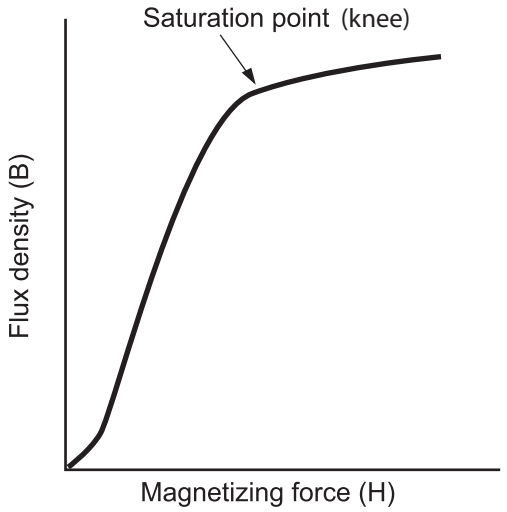


Figure 2—Magnetic saturation

Hysteresis loop

A material's magnetization curve may be plotted to show what happens to flux density as the magnetizing force is increased, decreased, increased in the opposite direction, and then returned to zero. The curve traced is the *hysteresis loop*. See Figure 3.

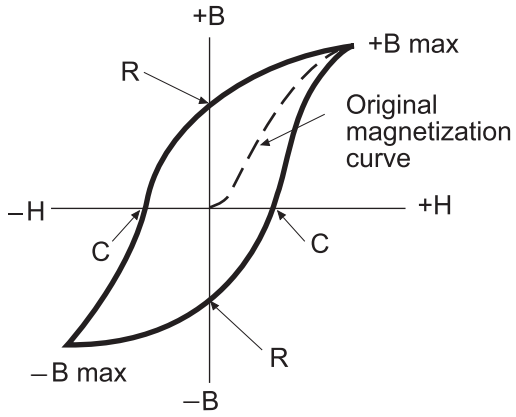


Figure 3—Hysteresis loop

The magnetizing force is usually controlled by varying the magnitude of the current through a magnetic coil. As the current is increased, the magnetizing force is increased. If the direction of the current is reversed, the direction of the magnetizing force is also reversed.

Notice that as the magnetizing force is increased and then decreased, the curve does not retrace back to zero. This is because some of the magnetism is retained by the material. All of the domains do not go back to their original position. This characteristic of retention of some of the magnetism is referred to as *retentivity*.

Hysteresis is the lagging of the flux density behind the magnetizing force. The magnitude of flux density for a given magnetizing force depends on the previous level of flux density.

Residual magnetism is the amount of flux density remaining in the magnetic material after the magnetizing force has been removed. The points labelled R in the hysteresis loop in Figure 3 show the flux density due to residual magnetism. To remove the residual magnetism, a magnetizing force must be applied in the reverse direction. This is done by reversing the current through the coil.

Coercive force is the amount of magnetizing force required to remove the residual magnetism. It is the amount of magnetizing force required to lower the flux density to zero. The points labelled C in Figure 3 show the coercive force.

The shape of the hysteresis curves show which ferromagnetic materials are best suited for which situations:

- Curves that are tall and narrow as in Figure 4(a) are best suited for electromagnets because they are easily magnetized and retain very little residual magnetism.
- Curves that are wider and relatively flat on top as in Figure 4(b) are well suited for use as permanent magnets. They have a high residual magnetism and require a strong coercive force to remove this magnetism.

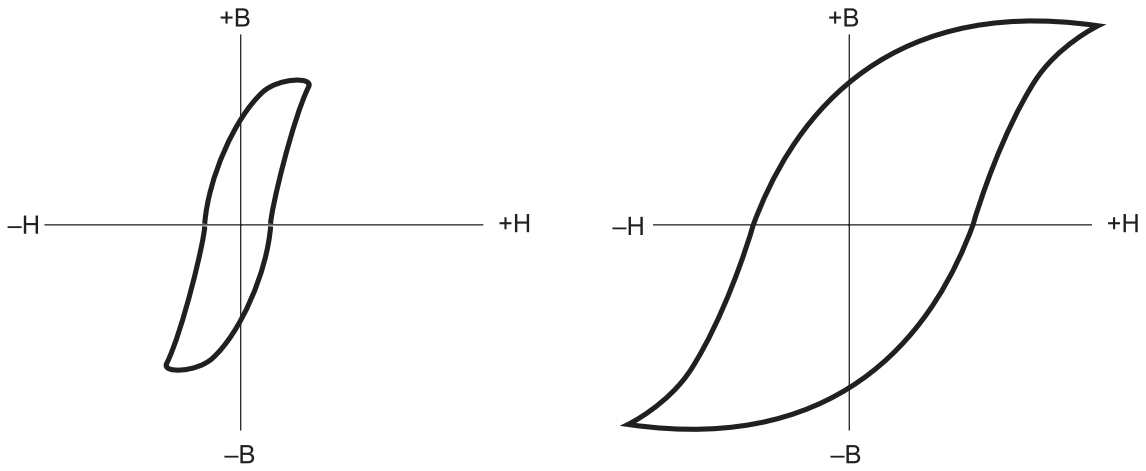


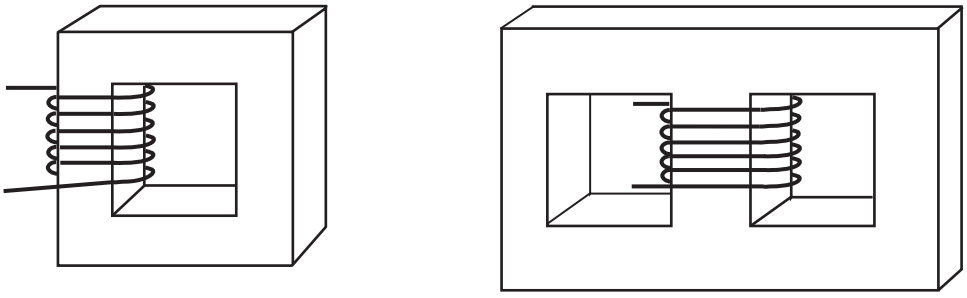
Figure 4—Hysteresis curves

- Curves like that in Figure 4(b) are not well suited for use in AC circuits. The large amount of energy required to reverse the magnetic flux direction results in high loss of heat energy. The amount of energy lost due to the constant reversals of the magnetic field in AC circuits is proportional to the area inside the curve. The larger this area, the greater the energy loss in the form of heat. This type of energy loss is referred to as *hysteresis loss*.

Magnetic cores

The cores of magnetic circuits are usually constructed from materials having high permeability and low reluctance. This means that flux lines are concentrated within the core material. This allows a higher flux density to be established with minimal magnetomotive force. Without a magnetic core, the flux lines spread out considerably as they leave the coil. This causes a very weak field because flux density is drastically decreased.

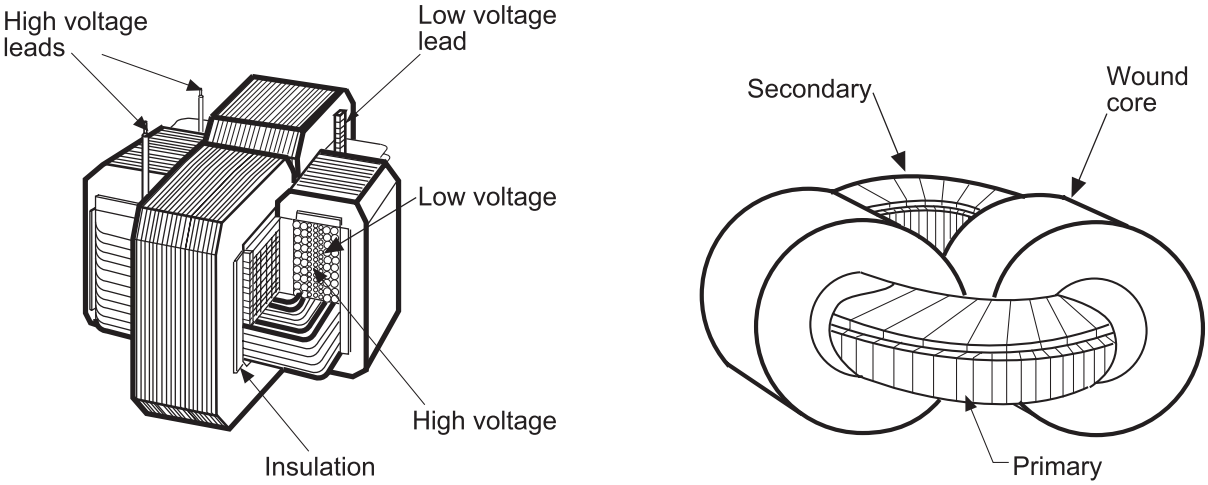
Forming the core into a complete loop concentrates the flux lines within the core even after they leave the coil ends. See Figure 5(a). This can be improved further by forming the core into two parallel loops. See Figure 5(b).



(a) Single loop (b) Two parallel loops

Figure 5—Magnetic cores

Some types of transformers have cores with four parallel loops as in Figure 6(a). This reduces leakage flux even more. Figure 6(b) shows a transformer with a wound core. This type of core is used for a number of reasons; one of the main ones is that it reduces leakage flux by eliminating sharp corners.



(a) Four parallel loops (b) Wound core

Figure 6—Magnetic cores

Core material is selected for its magnetic properties as well as for its electrical properties. Core materials used for AC magnetic circuits are chosen to have low retentivity and high electrical resistance.

- The low retentivity reduces heat losses associated with hysteresis.
- The high electrical resistance reduces the losses associated with something called *eddy current losse*s. You will study eddy current losses in a later Learning Guide.

Cores used in AC circuits are most often laminated. That is, they are made up of alternate layers of magnetic core material and an electrical insulator. You can see the laminations in Figure 6(a). These laminations also reduce eddy current losses.

Air gaps

Much of the machinery designed to operate on the principles of electromagnetism has moving parts near the magnetic circuits. (Some examples are motors, generators, loudspeakers, and relays.) Air gaps must be placed in the magnetic circuits to allow clearance for these parts to move. Since all of the magnetic flux must pass through the air gap, the air gap is in series with the circuit. Because air has a higher reluctance and lower permeability than the steel from which these devices are constructed, the air gap increases the total reluctance of the circuit.

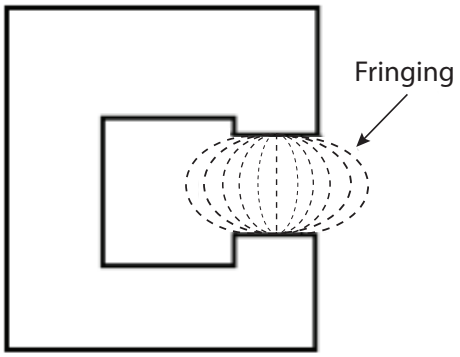


Figure 7—Fringing

Since the permeability of the air gap is lower than that of the rest of the circuit, the flux in the air gap tends to spread out. This spreading out of the flux lines is referred to as *fringing*. This fringing causes the flux density in the air gap to be lower than the flux density in the rest of the magnetic circuit. See Figure 7.

- Since the air gap is in series with the magnetic circuit, the total number of flux lines has not changed.
- If the length of the air gap is small (not more than 5 mm), as in motors and generators, it is possible to make a close approximation of the flux density in the air gap.
- If the length of the air gap is small, you can assume that each cross-sectional dimension has increased by a distance equal to the length of the air gap.

Figure 8 shows part of a magnetic circuit that contains an air gap. The flux density of the rest of the circuit and the dimensions of the air gap are given on the diagram. From this data you can calculate flux density in the air gap.

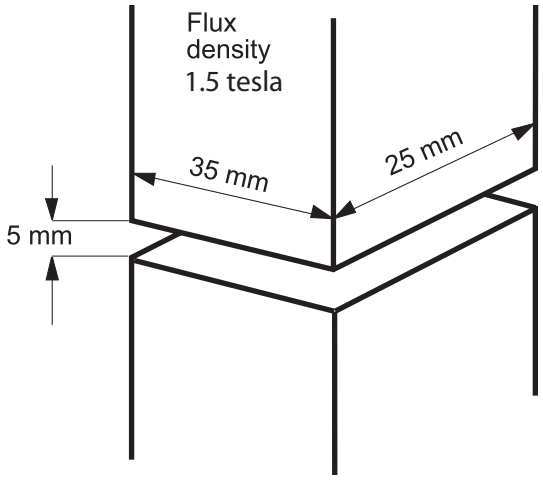


Figure 8—Air gap calculations

Example: Below is a calculation of flux density in the air gap illustrated in Figure 8.

core area $= 35\text{ mm} \times 25\text{ mm}$

$= 875\text{ mm}^2$

$= 875 \times 10^{-6}\text{ m}^2$

gap area $= (35\text{ mm} + 5\text{ mm}) \times (25\text{ mm} + 5\text{ mm})$

$= 40\text{ mm} \times 30\text{ mm}$

$= 1200\text{ mm}^2$

$= 1200 \times 10^{-6}\text{ m}^2$

total flux = flux density of core × core area

$= 1.5\text{ T} \times 875 \times 10^{-6}\text{ m}^2$

$= 1.3125 \times 10^{-3}\text{ Wb}$

$$\text{flux density of air gap} = \frac{\text{total flux}}{\text{gap area}}$$

$$= \frac{1.3125 \times 10^{-3}\text{ Wb}}{1200 \times 19^{-6}\text{ m}^2}$$

$= 1.094$ tesla

Air gaps are sometimes used in magnetic circuits with no moving parts to fine-tune or adjust the reluctance of the circuit. Often a piece of non-magnetic material such as fibreboard is placed in the air gap instead of air to assure an accurate gap length.

Table 1: Review of terms and units of magnetism

Quantity	Symbol	Equation	Unit	Abbreviation
Magnetomotive force (mmf)	F_m	$F_m = N \times I$	ampere-turn	A•turns
Flux	Φ	$\Phi = F_m / R_m$	weber	Wb
Reluctance	R_m	$R_m = F_m / \Phi$	ampere-turns per weber	A•turns/Wbw
Flux density	β	$\beta = \Phi / A$	tesla = webers per square metre	T
Magnetizing force	H	$H = F_m / L$	ampere -turns per metre	A•turns/m
Permeability	μ	$\mu = \beta / H$	webers per ampere-turn metre	Wb/A•turns m


Now do Self-Test 3 and check your answers.

Self-Test 3

1. The magnetic flux in a circuit is directly proportional to the _____ and inversely proportional to the _____ of the magnetic circuit.

2. Opposition to the formation of flux lines in a magnetic circuit is called _____ .

3. The point at which all of the domains in the magnetic material have aligned themselves with the magnetic field is referred to as _____ .

4. Residual magnetism is a measure of the amount of _____ remaining in the magnetic material after the magnetizing force has been removed.

5. The amount of reverse magnetizing force required to remove the residual magnetism is called the _____ .

6. The type of core material used for lifting electromagnets would have a _____ retentivity.

7. The spreading out of the flux lines in an air gap is referred to as _____ .

8. Magnetic cores that are constructed of alternating layers of magnetic material and electrical insulator are said to be _____ .

9. As the reluctance of a magnetic circuit is increased, the flux density of the circuit is _____ .

10. If the magnetomotive force applied to a magnetic circuit is increased, the flux density of the circuit is _____ .

11. The ease with which flux is set up in a unit length and cross-section of a material is referred to as the _____ .

12. The term for the lag of flux density behind magnetizing intensity is _____ .

13. Magnetic cores are usually constructed from materials with a high _____ and a low _____ .

14. The amount of energy lost due to the constant reversals of the magnetic field in AC circuits is referred to as _____ loss.

15. What form does this energy loss normally take?

_____

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 4:

Describe common applications of electromagnetic devices

Many devices use electromagnetism in their operation. This Learning Task will examine a few of these electromagnetic devices. When a wire is wound into a helical coil to create a stronger magnetic field, the coil is referred to as a *solenoid* (Figure 1). Solenoids are used extensively in electromagnetic devices.

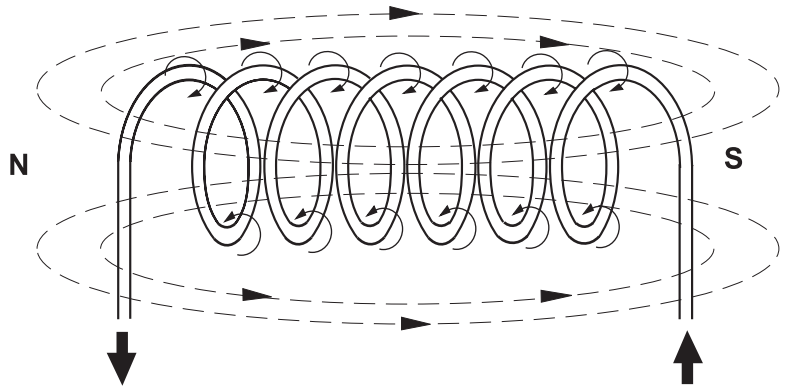


Figure 1—Solenoid

Lifting magnets

Lifting magnets use a solenoid wound around a magnetic material such as soft iron, which has low retentivity. See Figure 2. When a current is passed through the coil, the core becomes magnetized and poles are formed as shown. Pieces of ferromagnetic material are then attracted to the lifting magnet.

Once the lifted material has been moved to the desired location, a switch is opened to stop current flow. Because the core has a low retentivity, the magnetic field collapses when the current stops flowing and the material previously attracted to the lifting magnet is released and dropped.

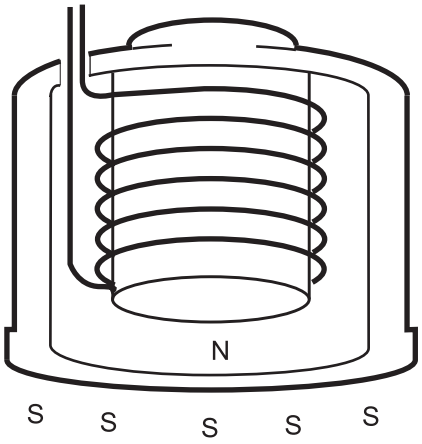


Figure 2—Lifting magnet

Relays

A relay is a type of electromagnetic switch. When current is passed through a coil, the magnetic field created attracts a spring-loaded armature (Figure 3). A movable electric contact is mounted on the armature and a stationary contact is mounted on the same base that holds the coil core.

- When current flows through the coil, the armature is attracted to the coil core.
- The two contacts come together, closing the switch.
- When the current stops flowing, the spring causes the armature to move away from the coil core.
- This separates the contacts, opening the switch.

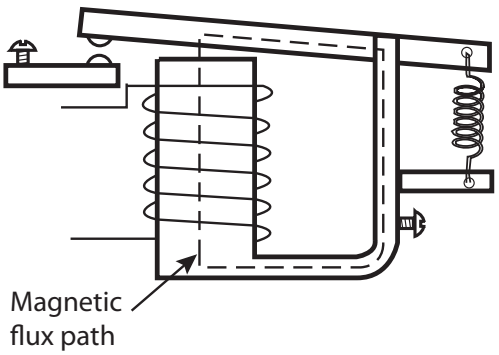


Figure 3—Relay

Relays are often used so that a small current can control a large current. By controlling a small current through the coil, the contacts can be opened and closed as required. The contacts are electrically isolated from the coil, so the contacts can be used to control the current flow in a completely different circuit.

Bells and buzzers

The operation of a bell is basically the same as that of a buzzer, so the two can be discussed together. Figure 4 shows a typical bell and buzzer mounted on the same frame.

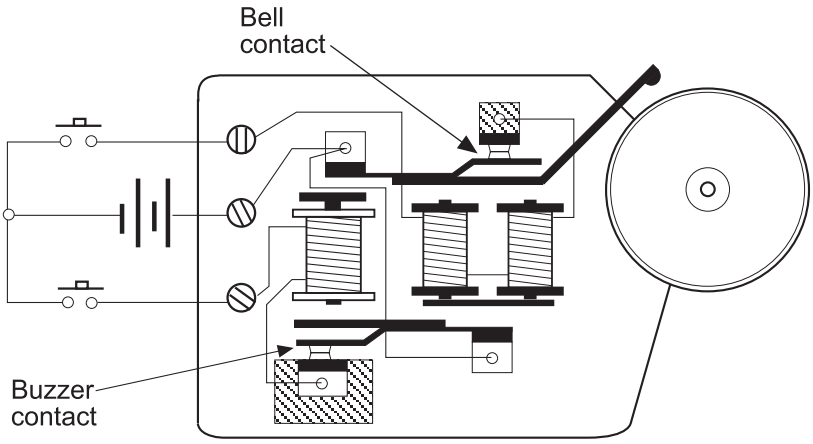


Figure 4—Bell and buzzer

- When the bell button is pressed, current flows from the battery through the switch; through the coils; through the bell contacts; and back to the battery.
- Current passing through the coils produces a magnetic field that attracts the armature.
- As the armature moves toward the coils, it strikes the bell and opens the bell contacts.
- As the bell contacts open, the current through the bell coils stops.
- The field collapses and the spring on which the armature is mounted pulls the armature away from the coils and re-closes the bell contacts.

- As long as the bell button is still pressed, the current starts to flow again and the cycle repeats itself.
- As the cycle repeats itself, the armature repeatedly strikes the bell.

The buzzer works the same way as the bell, except there is no bell for the armature to strike.

Field poles for motors and generators

Motors and generators are probably the most common use of electromagnetism. *Motors* use the electromagnetic effect to produce mechanical energy from electrical energy.

Generators use the magnetoelectric effect to produce electrical energy from mechanical energy.

Both of these machines require magnetic poles called *field poles* to operate. These field poles are created by passing a current through coils wound around a magnetic core called the *stator.* See Figure 5.

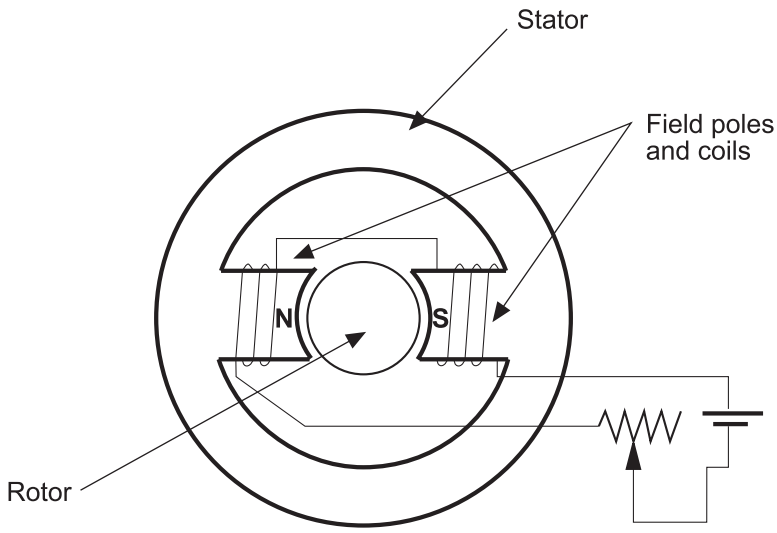


Figure 5—Field poles

A field rheostat controls the magnitude of the current through the field coils.

This varies the flux density of the field in order to:

- control speed and torque of a motor
- control magnitude of the voltage produced by a generator.

Now do Self-Test 4 and check your answers.

Self-Test 4

1. Define the term *solenoid*.

2. The core of lifting magnets is made from a material with _____ retentivity.

3. A _____ is a type of electromagnetic switch.

4. What is the purpose of the spring in the device mentioned in Question 3?

5. What happens to bell contacts as the armature strikes the bell?

6. How is the output voltage of a generator normally controlled?

7. What is the name of the device normally used to do this?

Go to the Answer Key at the end of the Learning Guide to check your answers.

Answer Key

Self-Test 1

1. magnetic flux

2. The magnetic lines of force do not collapse into the centre because of their mutual repulsion.

3. a. True

4. b. False

5. a. True

6. a. True

7. a. True

8. b. False

9. a. True

10. b. False

11. • using an electric current
    • stroking with a magnet
    • lining up with another magnetic field (such as Earth's) and tapping gently

12. • heating to the Curie temperature
    • using an alternating current and reducing the field strength slowly
    • tapping or vibrating the magnet

13. the alternating current method

14. the temperature at which a magnetic material loses its ferromagnetic properties

15. magnetic induction

Self-Test 2

1. yes

2. There is no point of convergence or divergence of the flux lines. There is no point of flux concentration.

3. The compasses also reverse direction.

4. reversal of the magnetic field direction

5. More lines of flux are formed and forced outward.

6. No, it becomes stationary.

7. more dense

8. The outer lines of force exert an inward force on the inner lines of force.

9. The lines of force collapse inward.

10. decreased, four

11. attract, repel

12. flux lines or the north pole of the coil

13. • spacing between coils in an air-core electromagnet
    • number of turns in the coil
    • magnitude of current flow through the coil
    • type of core material

14. ferromagnetic

15. air, wood, copper, aluminum, etc.

16. Vary the current through the coil.

17. rheostat

18. two

19. Strong magnetic forces occur between the bus bars if there is a short circuit.

20. dot

Self-Test 3

1. magnetomotive force, reluctance

2. reluctance

3. theoretical saturation
4. flux density
5. coercive force
6. low
7. fringing
8. laminated
9. decreased
10. increased
11. permeability
12. hysteresis
13. permeability, reluctance
14. hysteresis
15. heat

Self-Test 4

1. A solenoid is a wire wound into a helical coil for the express purpose of creating a stronger magnetic field.
2. low
3. relay
4. The spring pulls the armature away from the coil when the current stops flowing.
5. The contacts open.
6. The output voltage is usually controlled by varying a field rheostat thst controls the current flowing through the field coils. This varies the flux density of the field.
7. field rheostat



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