

CONSTRUCTION ELECTRICIAN APPRENTICESHIP PROGRAM

Level 1

Line D: Apply Circuit Concepts



D-1

LEARNING GUIDE D-1 USE ELECTRICAL CIRCUIT CONCEPTS

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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USE ELECTRICAL CIRCUIT CONCEPTS

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Learning Objectives

1. The learner will be able to describe the principles of electricity.
2. The learner will be able to apply the principles of electricity.
3. The learner will be able to describe electrical circuit components.
4. The learner will be able to apply electrical circuit components.

Activities

- Read and study the topics of Learning Guide D-1.
- Complete Self-Tests 1 through 20. Check your answers with the Answer Key provided at the end of this Learning Guide.
- Complete the Written Test for Learning Guide D-1.

Resources

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

- *Direct Current Fundamentals* 8th edition by Stephen L. Herman. Cengage Learning Inc.
- c22.1-09. *Canadian Electrical Code, Part 1* (21st Edition), Safety Standard for Electrical Installations. Canadian Standards Association (CSA), 2009.
- *Delmar's Standard Textbook of Electricity* 5th Revised Edition by Stephen L. Herman. Cengage Learning Inc.

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Please note that it is always the responsibility of any person using these materials to inform him/herself about the Occupational Health and Safety Regulation pertaining to his/her area of work.

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January 2011

Learning Task 1:

Describe the structure of matter

States and substances

Electricity is a form of energy. To understand electricity, it is important that you first understand the structure of matter. *Matter* is anything that occupies space or has mass. It can exist in any of three *states*: solid, liquid or gas.

There are many different types of matter. Each type has different physical properties and is classified into separate categories called *substances*. Two quantities of matter are said to be the same substance if their physical properties are identical. There are two general groups of substances: elements and compounds.

Elements

An *element* contains atoms of only one type. All matter is made up of elements. Each element has its own specific properties, which differ from those of other elements. These elements are often referred to as the building blocks of nature, and there are a little over 100 known. Of these, only 92 occur naturally and the rest are artificial. Some examples of elements are oxygen, hydrogen, carbon, copper and silver.

Compounds

A *compound* contains atoms of more than one type. One example is water, which consists of the elements hydrogen and oxygen. Another example is sugar, which consists of the elements carbon, hydrogen and oxygen.

Atoms and molecules

The smallest unit into which an element can be broken and still possess the properties of that element is referred to as an *atom*. Each atom has a letter symbol such as Na (sodium), S (sulphur) or C (carbon).

A *molecule* is the smallest independent unit into which a substance can be broken while still possessing the properties of that substance. Examples are H₂O (water), O₂ (oxygen) and C₁₂H₂₂O₁₁ (sugar).

The differences between an atom and a molecule are as follows:

- A molecule can be an independent unit of a compound or of an element, but an atom can only be the smallest unit of an element.
- A molecule must be independent but the atom does not have to be. For example, the smallest independent particle of the element oxygen contains two linked atoms. Oxygen can be broken down to a single atom and still retain its properties, but it will not remain as a single atom for any length of time.

The atom

The atom is composed of a dense nucleus surrounded by revolving electrons (rather like our sun surrounded by the planets). It is held together by electric forces. The properties possessed by elements are determined by the makeup of the atom.

All the atoms of a given element contain the same number of protons in their nucleus. The *atomic number* of any element is always equal to the number of protons in its nucleus. The atoms of each of the different elements contain a different number of protons in their nucleus. So, each element has a different atomic number.

For example, all hydrogen atoms contain one proton in their nucleus, all copper atoms contain 29 protons, and all carbon atoms contain six protons.

Figure 1 shows a model of a carbon atom.

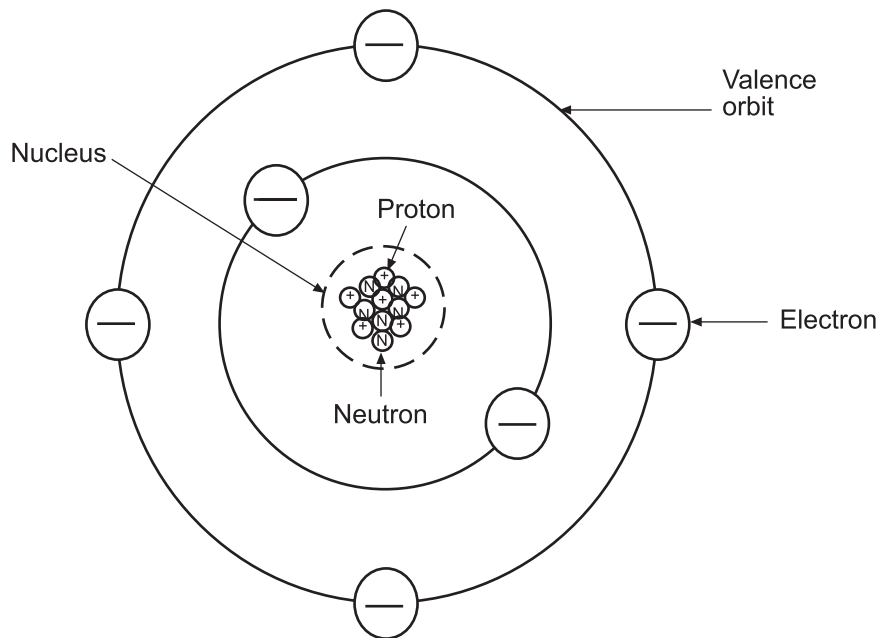


Figure 1—Carbon atom

The nucleus of the carbon atom contains six protons and six neutrons. Thus, the atomic number of carbon is six. As well, there are six electrons, which revolve around the nucleus of a carbon atom. The first or inner orbital contains two electrons. The outer orbital is half-filled with four electrons.

This outer orbital is referred to as the *valence orbital*. The term *valence*, which means ability to interact, is used because the electrons in this orbit interact with the electrons in the valence orbits of other atoms. In fact, the behaviour of electric circuits is quite dependent on the behaviour of these valence electrons, as you will see later in this Learning Task.

Orbital motion

From the orbital motion of the electrons around the nucleus it can be deduced that:

- Electrons, like any other body, must possess energy to be in motion. The energy, mass and velocity of a moving object are connected by the equation

$$E = \frac{mv^2}{2}.$$

- The mass of the electrons must be a fraction of the mass of the nucleus (otherwise nucleus and electrons would be moving a similar amount).
- There is a force of attraction between the nucleus and the electrons that holds the electrons in orbit.

The orbital motion of electrons can be compared to swinging in a circle a rock attached to an elastic band:

- If the rock is not given any energy, it will stay stationary.
- If the rock is given energy and starts moving, it will revolve around your hand the way the electrons revolve around the nucleus.
- If the rock were heavier than you, it is likely that as you exerted a force you would move rather than the rock. Similarly, if the electron were heavier than the nucleus, then the nucleus would revolve around the electron.
- If the elastic band were to break, the rock would no longer revolve around your hand, but would fly off in a straight line. This would also happen to an electron if there were no force of attraction between it and the nucleus.

Electron orbitals

Electrons revolve at high speed in their orbits around the atom's nucleus. Because of their great speed, centrifugal force tends to pull the electrons out of their orbit. Electrostatic forces, which you will learn about in Learning Task 2, keep the electrons from breaking away. However, if sufficient outside force is applied to an electron to aid the centrifugal force, the electron can be freed from the atom.

All electrons do not possess the same amount of energy. Electrons farther from the nucleus have more energy than electrons closer to the nucleus. If they all possessed the same energy, they would all be in the same orbit. In the previous analogy, if more energy is supplied to the rock, the rock speeds up, the centrifugal force increases, the elastic band stretches, and the rock revolves in a larger orbit.

The fact that electrons closer to the nucleus have less energy than electrons in the valence orbit means that the electrons in the inner orbits are difficult to free from the atom.

Therefore, you can neglect the electrons in the inner orbits and concern yourself only with those in the outer valence orbit when you consider removal of electrons from the atom.

Electrons fill the orbits in a very definite pattern:

- The inner shell fills to a maximum of two electrons.
- The next orbit fills to a maximum of eight electrons.
- The third orbit can hold a maximum of 18 electrons.
- The fourth can hold a maximum of 32 electrons, and so on.

The general formula is that the n^{th} shell can in principle hold up to $2 \times n$ squared electrons. Although that formula gives the maximum in principle, in fact that maximum is only achieved (by known elements) for the first four shells (K, L, M, N). No known element has more than 32 electrons in any one shell.

The outer valence orbit can never fill to more than eight electrons.

Figure 2 shows the maximum numbers of electrons for each orbit.

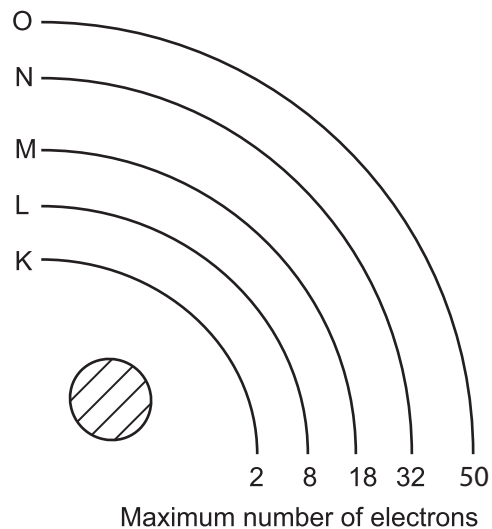


Figure 2—Electron orbitals

Freeing electrons

As energy is given to the rotating rock, its velocity increases and the centrifugal force increases. The elastic band stretches and the size of the orbit increases. Eventually the centrifugal force is too great for the elastic band, and it breaks, freeing the rock.

The orbiting electron is similar: as more energy is provided to the electron, its centrifugal force increases until finally it breaks free from the electrostatic force between itself and the nucleus. When this happens, the electron becomes a *free electron*.

Atoms become stable if they have eight electrons in their valence orbit. This is called a *stable octet*. Atoms automatically adjust to the most stable state possible. Those atoms with fewer than four valence electrons give them up relatively easily. Atoms with more than four valence electrons attract more electrons from their surroundings to complete a stable octet.

Any energy added to the electrons in the valence orbit is distributed equally among all those electrons. This means that less energy is required to remove an electron from its orbit if it is the only electron in the orbit. More energy is required if there are other electrons in the same orbit. The more electrons there are in the valence orbit, the more energy is required to free an electron.

Conductors

Materials that have electrons that are easily freed are called *conductors* of electricity. Atoms that have one to three valence electrons are conductors. However, what makes one conductor better than another is the number of free electrons per unit volume of the material. The greater the number of free electrons per unit volume, the better electrical conductor the material is. For example, a cubic centimetre of copper contains approximately 8.5×10^{22} free electrons. Silver has about 5% more free electrons per unit volume, and is about 5% better as a conductor than copper. Most metals are good conductors.

Insulators

Insulators are materials from which electrons are very difficult to free. Atoms that have five to eight valence electrons are insulators. To free electrons, much more energy must be supplied to insulators than to conductors. Examples of elements that are insulators are the inert gases, such as helium.

Semiconductors

Semiconductors are those elements that are neither good conductors nor good insulators. They are the elements with exactly four valence electrons. Examples are carbon, silicon, germanium, tin and lead. Later in your studies you will learn that adding impurities to semiconductors can produce some very useful electrical attributes.



Now do Self-Test 1 and check your answers.

Self-Test 1

1. A substance that is made up of atoms of more than one type is a _____ .
2. Anything that occupies space or has mass is referred to as _____ .
3. The atomic number of an element refers to the number of _____ in the _____ of the atom.
4. What is the maximum number of electrons that can be in the valence orbital of an atom?

5. In orbits farther from the nucleus, the energy possessed by the electrons:
 - a. increases
 - b. decreases _____
6. An electron that has broken loose from its atom is a _____ electron.
7. Semiconductors contain _____ valence electrons.
8. Most metals are good _____ .
9. The smallest *independent* portion that a substance can be broken down into and still possess the properties of the substance is a _____.
10. The smallest portion an element can be broken down into and still possess the properties of that element is referred to as an _____ .

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

Learning Task 2:

Describe the concepts of electric charge and current flow

By the year 1900, researchers studying electricity had shown that there is a fundamental unit of charge. Scientists had also shown the existence of negatively charged particles and positively charged particles, which they called electrons and protons, respectively. It was discovered that:

- The protons had a charge equal but opposite to that of electrons.
- Each proton had a charge equal to that of every other proton.
- Each electron had a charge equal to that of every other electron.

By 1911 Ernest Rutherford had demonstrated the existence of atomic nuclei. Two years later, a Danish physicist named Niels Bohr presented a model of the atom similar to the one used in Learning Task 1, where the negatively charged electrons revolve around the positively charged nucleus.

Charged bodies

A body can possess a positive charge, a negative charge or no charge at all. If it possesses no charge at all, it is said to be *neutral*. The type of charge a body has depends upon the numbers of electrons and protons the body has.

For example, a neutral atom has the same number of protons in the nucleus as it has electrons in the orbitals that surround the nucleus. The atom can be given a negative charge by adding electrons to the orbitals, or it can be given a positive charge by removing electrons from the orbitals. When the atom is given a charge in this way, it is said to be *ionized* or is called an *ion*. An atom with a negative charge is called an *anion*, and an atom with a positive charge is called a *cation*.

In larger bodies, which contain many, many atoms, the charge on the body is determined the same way as for atoms. If the body contains more electrons than protons, the charge on the body is negative, and if the body contains fewer electrons than protons, the charge on the body is positive.

Note that an electron has a mass that is a fraction of that of a proton. Also, the protons are very firmly bound to the nucleus. Therefore, it is the electrons, not the protons, that are added or removed.

The fundamental laws of charged bodies

There are two fundamental laws governing the interactive behaviour of charged bodies: one on the direction and one on the size of the forces.

The first law governs the force of attraction between negatively charged electrons and the positively charged nucleus. This force keeps the electrons in their orbit.

1. *Like charges repel and unlike charges attract.*

This law means that negatively charged bodies repel other negatively charged bodies, but attract positively charged bodies. It also means that positively charged bodies repel other positively charged bodies, but attract negatively charged bodies.

The second law governs the strength of the force between charged bodies.

2. *Coulomb's law of electrostatic charges.*

The force between two charges at rest is directly proportional to the product of the magnitudes of the charges. It is also inversely proportional to the square of the distance between them.

Written mathematically, the law is:

$$F = \frac{k \times Q_1 \times Q_2}{d^2}$$

F = force in newtons

k = a constant depending on the medium between the charges

Q = the charge in coulombs

d = the distance between the charges in metres

By looking at the mathematical formula it is apparent that:

- If either or both of the charges is increased, the force increases.
- If either or both of the charges is decreased, the force decreases.
- If the distance between the charges is doubled, the force decreases to one-quarter of what it was.
- If the distance between the charges is reduced by one-half, the force is increased by four times.
- By the first law, if the two charges are alike, the force is one of repulsion.
- If the two charges are unlike, the force is one of attraction.

Field forces

The force between electric charges is referred to as a field force because, like the force of gravity, it acts at a distance without contact. Just as there is a gravitational field around the Earth, there is an *electrostatic field* (or electric field) around a charged body. The electrostatic field is defined as the region in which an electric charge is acted upon by an electrical force.

The electrostatic field is made up of invisible lines of force. These lines of force represent the path along which a theoretical, weightless, electrically charged particle travels in moving from one charged object to another.

These lines of force always begin and end on charged bodies and always meet the surface of the bodies at right angles. The lines have a direction that is the same direction that a weightless positively charged particle would travel in going from one charged body to the other.

Electrical polarity

Polarity is a very important electrical concept. It refers to the charge at one point with respect to another. When you are discussing polarity, it is critical to remember that you are talking not about only one point, but about the relative state between two points.

Consider five cups of water, all at different temperatures:

Cup A is heated to 40°C (degrees Celsius).

Cup B is heated to 30°C.

Cup C is at room temperature, 20°C.

Cup D is cooled to 10°C.

Cup E is cooled to 1°C.

If room temperature is considered to be neutral, any temperature above room temperature has positive heat with respect to neutral, and any temperature below room temperature is negative with respect to neutral. So any temperature above 20° is called positive and any temperature below 20° is called negative. This expresses the *polarity* of the heat of one cup of water with respect to another standard, in this case with respect to 20°.

Therefore,

- Cups A and B are positive with respect to cup C.
- Cups D and E are negative with respect to cup C.

Now consider the heat of cup A with respect to cup B. The temperature of cup B is now the reference point rather than the room temperature. Cup A is above cup B in temperature, so it can be said that the temperature of cup A is positive with respect to cup B. If cup A is used as the reference point, then it can be said that the temperature of cup B is negative with respect to cup A. The point is that polarity is relative and depends on which point is chosen as the reference.

Now apply the analogy to electric charge. Consider five copper pennies:

- Penny A is missing 100 of its electrons (positive charge).
- Penny B is missing 50 of its electrons (positive charge).
- Penny C has an equal number of electrons and protons (neutral).
- Penny D has an extra 50 electrons (negative charge).
- Penny E has an extra 100 electrons (negative charge).

If penny C is considered as the reference point, pennies A and B are positive with respect to C, and pennies D and E are negative with respect to C. Some other relationships are:

- Penny A is positive with respect to penny B.
- Penny B is positive with respect to penny D.
- Penny D is positive with respect to penny E.
- Penny B is negative with respect to penny A.

How bodies become charged

There are three ways in which a body may receive a charge: by friction or contact, by conduction and by induction.

Friction or contact

When two dissimilar substances are rubbed together, electrons are transferred from one substance to the other. This transfer results in a charge. If the substances are insulators, the charge is retained after the substances are separated. It has been shown that if two highly polished, dissimilar substances are brought into contact and separated without rubbing or friction, the same effect occurs. For this reason, it is called *charging by contact*. Scientists believe that all the rubbing does is increase the area of contact.

Conduction

If a charged body comes into contact with an uncharged body, some of the charge is transferred to the uncharged body. When the two bodies are separated, they both possess the same type of charge. A common example of this type of charge transfer is the arc that jumps between the door handle and your hand on a dry winter day. Some of the charge your body has accumulated by friction is transferred by contact to the neutral handle.

Induction

There are three steps in charging by induction:

1. If a negatively charged object is brought close to a neutral object, the electrons at the end of the neutral object that is closest to the negatively charged object are repelled to the end farthest away from the charged object.
2. If the end of the neutral object farthest from the charged object is then attached to ground with a wire, electrons flow from the uncharged object through the wire into the ground.
3. If the wire is then removed from the neutral object, it will be left with a net positive charge because of the removed electrons.

The above charge is said to be *electrostatically induced*. The process is called *electrostatic induction*.

Neutralizing a charge

If two substances having equal but opposite charges are brought into contact, electrons transfer from the substance with the negative charge to the substance with the positive charge, and both substances are neutralized.

Another way to neutralize a charge is to bring the object into contact with the Earth. The Earth is such a large mass with respect to the objects on it that the small charges flowing to and from the Earth have no noticeable effect on its charge. Many devices and electrical systems are connected directly to the Earth to prevent a dangerous charge from building up on them.

Useful applications of electrostatic charge

There are many useful applications for electrostatic charge. A few examples follow.

Painting

Two problems that occur in spray painting are uneven paint thickness on the object being painted and paint waste due to over-spray. By charging the object to be painted with one charge and the paint with the other charge, over-spray is reduced and a more uniform paint thickness achieved.

Sandpaper manufacturing

The sand is given one charge and the paper is given the opposite charge. The sand is attracted to the paper, but the sand particles repel each other, which causes them to stand on end while the glue is applied. This gives the sandpaper a much more abrasive surface.

Smoke precipitator and air filters

A screen in the smoke stack is given a charge so that, as the smoke passes through the screen, the particles of soot are attracted to the screen and collected. The same principle is applied to air filters.

Xerography

Selenium is a semiconductor material that conducts better when exposed to light. This fact is used to reproduce documents.

Xerography, long outdated by modern technology, used a process by which:

- A drum of selenium is constructed over an aluminum cylinder and the outside is given a positive charge.
- The drum turns as the original document is passed over it.
- A light is positioned to shine on the paper so that reflected light strikes the drum.
- Where the light strikes the dark print on the original, light is not reflected to the drum. This produces a reverse image of the original on the drum.
- Where the light has struck the selenium, the selenium conducts and the charge is neutralized.
- The portion where the image did not reflect the light remains charged.
- As the drum turns, it attracts the charged print powder to the drum in the reverse image of the original.
- The copy paper is passed under the drum as it turns and the print powder is deposited on the paper in the image of the original.
- After leaving the drum the copy passes near a heater, which melts the print powder onto the copy page.

Hazards of electrostatic charge

Electrostatic charge can create hazardous situations:

- Lightning is a potential danger caused by the accumulation of electrostatic charge.
- Anything that can cause a spark to jump in the area of fuel handling has the potential to cause a fire or an explosion. If an electrostatic charge does not exist before the start of fuel transfer, it may be caused during the fuel transfer simply because of the contact and separation of the fuel droplets. To avoid this situation, bond the two fuel containers together so that their charges equalize before the transfer of fuel.

Random electron flow versus directed electron flow

When atoms combine to form a piece of metal, they form what is called a *metallic bond*. In this type of bond, each atom shares its valence electrons with the other atoms around it. The electrons form a kind of cloud, with the electrons drifting from atom to atom in a random manner. The net flow of charge always balances or equals zero, and this is referred to as *random electron flow*. Nuclei are attracted to the electron cloud but repelled by other nuclei, forming a distinct geometric pattern, as shown in Figure 1.

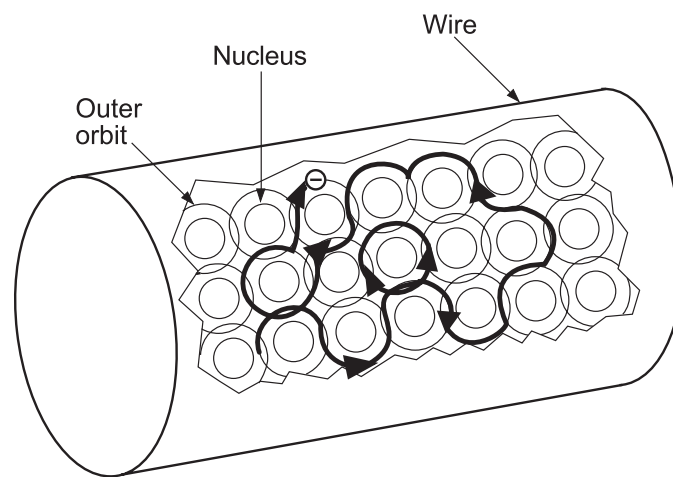


Figure 1—Random electron flow in a conductor

If a surplus of electrons (negative charge) is placed at one end of the conductor and a deficiency of electrons (positive charge) is placed at the other end, a *directed electron flow* will occur, as shown in Figure 2 on the next page. The electrons in the conductor are repelled by the negative charge and attracted by the positive charge. This causes a flow of *free electrons* from the negative end of the conductor to the positive end of the conductor. As the free electrons leave the conductor at the positive end, they are replaced by electrons entering the conductor at the negative end.

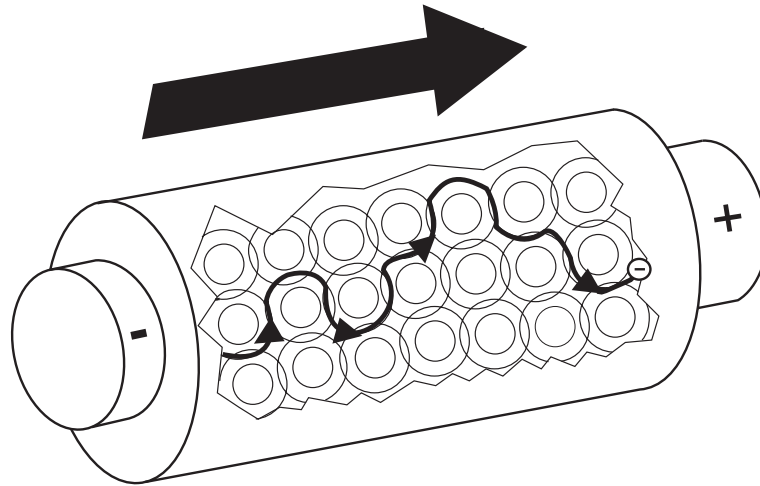


Figure 2—Directed electron flow in a conductor

This can be thought of as though, in leaving an atom, a free electron leaves a hole in the positively charged ion left behind. This gap attracts another negative electron to fill it. This process repeats itself many times over as the electron moves down the conductor from the negative end to the positive end.

This directed flow of electrons is referred to as an *electric current*. An electric current is the directed flow of electrons through a conductor. *In these learning materials, current flow is considered to be an electron flow that is from negative to positive.*

Note: When Benjamin Franklin assigned the labels of positive and negative electricity back in about 1750, he thought that electricity was caused by the flow of an electric fluid. He believed that positive electricity was caused by a surplus of the fluid and that negative electricity was caused by the deficiency of fluid. Therefore, engineers and many textbooks still refer to current flow as being from positive to negative. This is referred to as *conventional current flow* and may be thought of as the flow of holes left behind as the electron travels through the conductor. As the electrons move from negative to positive, the holes move from positive to negative. In these learning materials we use the convention of electron flow from negative to positive.



Now do Self-Test 2 and check your answers.

Self-Test 2

1. According to Coulomb's law, if the distance between two point charges is decreased by four times, the force between the charges will _____ by _____ times.
2. An atom that has a positive charge possesses _____ electrons than protons.
3. Like charges _____ and unlike charges _____ .
4. List five useful applications of electrostatic charge.

5. List two situations in which electrostatic charge can create a potential hazard.

6. List three ways in which a body may receive an electrostatic charge.

7. The direction of electron flow is from _____ to _____ .
8. A force that acts at a distance without physical contact is referred to as a _____ force.
9. _____ refers to the charge at one point with respect to another.
10. If one of two charges has its magnitude doubled, then the force between the two charges will _____ by _____ times.

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

Learning Task 3:

Describe methods of producing electricity

In the previous Learning Task you learned that if there is a surplus of electrons at one end of a conductor and a deficiency at the other end, a current flows in the conductor. There are devices that create this difference in charge so that a current will flow. These devices are referred to as *sources of electromotive force*.

Electromotive force

Electromotive force (emf) is defined as the work per unit charge done by a source of energy on electric charges, to move them against an electric field. The charges in this case are the electrons. When work is done on electrons, energy is given to them and they can use this energy to do work. As you learned earlier, energy is transferred to an electron to remove it from its valence orbital and atom.

Sources of emf are devices that change other forms of energy to electrical energy. Six of the most common types of emf sources are discussed here:

- Friction
- Chemical
- Pressure
- Heat
- Light
- Magnetism

Friction

When two dissimilar materials are rubbed together, one material can transfer some of its electrons to the other. This is known as the *triboelectric effect*. On the surface of a material, there are many atoms that cannot combine with other atoms as they do inside the material. This means that the surface atoms have some electrons that are not tightly bound.

One theory is that when the materials are rubbed together, the heat energy of friction is transferred to the electrons and frees them. But experiments have shown that only contact pressure is needed to cause the electrons to move from one material to the other. If the materials are insulators, the charge is retained after contact stops.

One device that uses the triboelectric effect is the Van de Graaff generator. This device produces the high voltages necessary to test lightning protection equipment and to split atoms in particle accelerators.

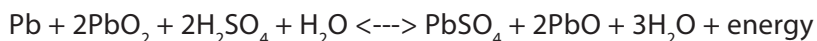
Chemical

Energy is contained in the bonds that exist between the different elements in molecules. When the molecules are broken and the elements recombine to form different molecules, energy is either absorbed or given off.

It is natural for all things to tend to move from a high energy state to a lower energy state. In the cells of a battery, the ions of a molecule disassociate and recombine to form different molecules whose bonds contain less energy. The excess energy is given off in the form of electrical energy or emf.

If the battery cell is of the secondary type, it is possible to reverse the reaction by supplying the cell with electrical energy, which the cell can store.

This effect is a part of what is known as the *electrochemical effect*. An example of this chemical process and its equation is the charging and discharging of a simple automobile battery. In this process lead (Pb) and lead dioxide (PbO₂) combine with sulphuric acid (H₂SO₄) and water (H₂O) to give lead sulphate (PbSO₄), lead oxide (PbO), water and energy.



Pressure

The interaction of electrostatic and mechanical stresses within certain crystals is called the *piezoelectric effect*. Mechanical stress of a crystal causes displacement of electrons. This results in an electron deficiency on one side of the crystal and a surplus on the other. Thus, pressure on the crystal can cause current to flow. The opposite effect can also occur: if a crystal is electrically stressed, it is distorted mechanically.

This effect is used in ceramic phonograph cartridges and ceramic microphones. The effect is also used for measuring the shifting of the tectonic plates of land.

Heat

The *thermoelectric effect* takes place when a junction of two dissimilar metals is heated. For example, when a junction of copper and zinc is heated, the copper takes on a positive charge and the zinc takes on a negative charge. The greater the heat, the greater the generated emf. This type of device is referred to as a *thermocouple* and is often used as a temperature-sensing device. When more than one of these thermocouples are connected in series, it is called a *thermopile*.

Light

Scientists describe light as made up of small particles of energy called *photons*. Light also behaves as waves that contain energy. When the light strikes the surface of some materials, it gives up this energy to the electrons in the material. The extra energy causes the electrons to leave their atoms, and current to flow. This is known as the *photovoltaic effect*. The device that does this is known as the *photovoltaic cell*. Common applications of these cells include calculators and satellites.

Magnetism

This is the method by which most of the electrical energy we use is produced. Magnetism and moving electric charge are inseparable. Whenever one exists, the other must exist as well. By moving a magnetic field in a certain direction relative to a conductor, an electric field is produced. This field is in a specific direction with respect to the magnetic field. The electric field causes separation of the positive and negative charges in the conductor, so that a voltage is induced across the ends of the conductor.

This *magnetoelectric effect* is what is used to produce the electricity that the power authority delivers to our homes and businesses. It is the principle by which *generators* and *alternators* produce electricity.

The opposite phenomenon also occurs: electrical energy is used to produce magnetic fields, which in turn produce mechanical energy. This is referred to as the *electromagnetic effect*, and is the principle by which *electric motors* produce motion.

All six of these sources of emf achieve the same thing. They separate charge by:

- Imparting energy to the electrons
- Pushing them against an electrostatic field
- Causing a surplus of electrons (negative charge) at one terminal of the source and a deficiency of electrons (positive charge) at the other terminal

In a sense the process can be likened to compressing a spring. The energy stored in the compressed spring can be used later to do useful work. The same is true of the separated charges: they store energy that can be used to do useful work.

It is important to note that all the methods of producing emf obey the *law of the conservation of energy*. This law states that energy may be neither created nor destroyed. Electrical energy always comes from some other form of energy. The source of emf is simply the device that makes the conversion from some other form of energy to electrical energy.



Now do Self-Test 3 and check your answers.

Self-Test 3

1. Devices designed to change other forms of energy into electrical energy are referred to as _____ of electricity.
2. List six methods of producing electricity.

3. The term *triboelectric effect* refers to the generation of electricity by _____ .
4. The term *piezoelectric effect* refers to the generation of electricity by _____ .
5. The device used to produce electricity by heating a junction of two dissimilar metals is referred to as a _____ .
6. The device that generates electricity from the sun's energy is called a/an _____ .
7. The work-per-unit-charge done by a source on the electric charges, to move them against the electric field, is referred to as _____ .
8. Most of the electrical energy used in your home is produced by _____ .
9. State the law of conservation of energy.

10. The solar cell in a simple calculator is called a _____ .

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

Learning Task 4:

Describe electrical quantities units and symbols

To go any farther in the study of electricity, you need to know some terms for the quantities in electricity. In this Learning Task you will learn about five different quantities in electricity:

- Charge
- Current
- Voltage
- Resistance
- Power

You will learn what they refer to, their symbols, the units they are measured in, and the abbreviations for the units. Also, you will learn about how the five quantities relate to each other.

Charge

First you need a method of comparing the charge on one body to the charge on another body. The letter Q is used to represent the quantity of charge. It seems to make sense to use the charge on one electron. However, the charge on a single electron is too small to be a practical unit of charge. For this reason, the unit of charge used is the charge on 6.24×10^{18} electrons. This number, which seems an odd choice, results from the choices made for other units.

- The name given to the quantity of charge on 6.24×10^{18} electrons is the *coulomb*.
- This unit is named after a famous physicist, Charles Augustin Coulomb.
- The abbreviation used for the unit of electric charge is C.

Current

The next quantity you need for the purpose of discussing electric circuits is the rate of flow of charge. The term *current* refers to the rate of flow of charge. The symbol for the rate of flow of charge is I (probably for intensity).

- The unit of current is the *ampere*, named after Andre Ampere.
- The abbreviation for the unit is A.

When 1 coulomb of charge crosses a given point in a conductor in 1 second, current is said to flow at the rate of 1 ampere.

$$1 \text{ A} = 1 \text{ C/sec}$$

- 1 ampere is equal to 1 coulomb per second.
- 1 ampere is equal to 6.24×10^{18} electrons per second.

Voltage

Energy is needed to move an electron from the positive terminal of the source to the negative terminal. There is a force of attraction between the electron and the positive terminal, and there is a force of repulsion between the negative terminal and the electron.

Anytime work is done on a body to move it against a force, that body is given energy. The same is true for the electron. As the electron is moved against a force to get it from the positive terminal to the negative terminal, the electron is given energy. This means that electrons at the negative terminal of the source have a higher energy level than those at the positive terminal. This potential energy difference is referred to simply as the *potential difference*.

The potential difference between any two points in an electric circuit is the rise or fall in potential energy involved in moving 1 coulomb of charge from one point to another.

- The abbreviation for potential difference is PD.
- The unit of potential difference is the *volt*, named after Alessandro Volta.
- The abbreviation for the volt is V.

When the energy used to move 1 coulomb of electric charge from one point to another in an electric circuit is 1 joule, the potential difference between the two points is 1 volt.

$$1 \text{ V} = 1 \text{ J/C}$$

That is, 1 volt is equal to 1 joule per coulomb.

If it takes 3 joules of energy to move 1 coulomb of charge between two points, the potential difference between the points equals 3 volts.

Within an energy source there is a *potential rise*, and within the rest of the circuit there is a *potential drop*. This means the source gives energy to the electrons and the electrons give up this energy to the rest of the circuit.

When the source gives energy to the electrons, it is like pushing them against a big spring inside the source. This provides the push that forces the electrons through the circuit.

- This push, or potential rise, supplied by the source is referred to as the *electromotive force*, abbreviated emf.
- The potential drop that occurs everywhere else in the circuit is referred to as the *voltage drop*.

The term *voltage* is lazily applied to the quantities of both potential difference and electromotive force. The abbreviation used for both quantities is E. The abbreviation V is also used.

Resistance

If nothing opposed the flow of current in a circuit, then, according to Newton's first law, once the current started it would never stop. Just as friction opposes motion around you, there is an electrical quantity, called *resistance*, that opposes the flow of electric current. The abbreviation for the quantity of resistance is R.

- The electrical unit of resistance is the ohm, named after Georg Simon Ohm.
- The abbreviation for this unit is the Greek letter omega, Ω .

An electric circuit has a resistance of 1 ohm when the applied emf of 1 volt causes a current to flow at the rate of 1 ampere.

$$1 \Omega = 1 \text{ V/A}$$

That is, if 1 volt is applied across a device and $\frac{1}{2}$ of an ampere flows, the device has a resistance of 2Ω . Another example would be that if 3 volts are applied across a device and 1 ampere flows, the device has a resistance of 3Ω .

Power

If a force is applied to an object that causes the object to move in the direction of the applied force, then it is said that *work* is being done on that object. The rate at which the work is done is referred to as *power*. The abbreviation for the quantity of power is P.

When work is done on an object, the object receives energy. So power can be defined as the rate of doing work, or as the rate of energy transfer.

- The unit of power is the *watt*, named after James Watt.
- The abbreviation for this unit is W.

The definition of the watt is that if work is done at the rate of 1 joule per second, then the power (rate of doing work) is 1 watt.

$$1 \text{ W} = 1 \text{ V} \times 1 \text{ A}$$

That is, the power (watts) is equal to the voltage (volts) times the current (amps).

Table 1: Electrical quantities and units

Electrical quantity	Quantity symbol	Electrical unit	Unit abbreviation
Charge	Q	coulomb	C
Power	P	watt	W
Resistance	R	ohm	Ω
emf or PD	E	volt	V
Current	I	ampere	A



Now do Self-Test 4 and check your answers.

Self-Test 4

1. The charge on 6.24×10^{18} electrons is referred to as a _____ .
2. If 4 coulombs of charge pass a given point in a conductor over a period of 2 seconds, current is flowing at the rate of _____ amperes.
3. If 3600 joules of work are required to move 6 coulombs of charge from point A to point B, the potential difference between the two points is _____ volts.
4. The term used to represent the opposition to current flow in an electric circuit is _____ .
5. Complete the following chart:

Electrical quantity	Quantity symbol	Electrical unit	Unit abbreviation
Charge			
	P		
		ohm	
emf or PD			
			A

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

Learning Task 5:

Perform calculations using Ohm's law and Watt's law and motor efficiency

Ohm's law and Watt's law

Ohm's law and Watt's law express how electrical units are related. The two laws combine in various ways to allow the solution of electrical problems.

Ohm's law

The current flowing in an electric circuit is directly proportional to the applied voltage and inversely proportional to the resistance of the circuit.

In direct proportion means that if the applied voltage is doubled, the current will also double. If the applied voltage is decreased to half of its previous value, the current will also decrease to half of its previous value.

Inversely proportional means that if the resistance is doubled, the current will decrease to half of its previous value. If the resistance is reduced to half of its previous value, the current will double.

In equation form, Ohm's law is:

$$I = \frac{E}{R}$$

which transposes to two other forms:

$$E = I \times R \quad \text{and} \quad R = \frac{E}{I}$$

Watt's law

The power in a circuit equals the product of the voltage and the current in the circuit.

This means that to find the power in a circuit, all you have to do is multiply the voltage by the current. In equation form, Watt's law is:

$$P = E \times I$$

This equation can be transposed to two other forms:

$$E = \frac{P}{I} \quad \text{and} \quad I = \frac{P}{E}$$

Ohm's law and Watt's law combine, using substitution and transposition, to yield a total of 12 equations, six of which have already been stated. The other six are:

$$E = \sqrt{P \times R} \quad P = I^2 \times R \quad P = \frac{E^2}{R}$$

$$R = \frac{P}{I^2} \quad R = \frac{E^2}{P} \quad I = \sqrt{\frac{P}{R}}$$

Solved problems

1. If the voltage applied across a light bulb is 120 V and the resistance of the light bulb is 144 Ω , what current flows through the light bulb?

$$I = \frac{E}{R} = \frac{120\text{V}}{144\Omega} = 0.833\text{A}$$

2. What is the power of the light bulb in the above question?

$$P = E \times I = 120\text{V} \times 0.833\text{A} = 100\text{W}$$

3. How much current would a 200 W light bulb draw from the same 120 V source?

$$I = \frac{P}{E} = \frac{200\text{W}}{120\text{V}} = 1.67\text{A}$$

4. A baseboard heater connected to a 240 V source produces heat at the rate of 1500 W. What is the resistance of the heater?

$$R = \frac{E^2}{P} = \frac{(240\text{V})^2}{1500\text{W}} = 38.4\ \Omega$$

5. At what rate would heat be dissipated if a heater with the same resistance was connected to a 120 V source?

$$P = \frac{E^2}{R} = \frac{(120\text{V})^2}{38.4\ \Omega} = 375\text{W}$$

Electrical units with metric prefixes

In the study of electricity many of the quantities that you will deal with are very large numbers or very small numbers. For example, transmission lines often transmit at voltages of 500 000 volts, and some computers deal in currents as small as 0.000 000 001 amperes. These numbers become very cumbersome. As well, it is very easy to miss a zero when writing the numbers out.

One way to deal with this problem is to express all of the numbers in terms of powers of 10. This is scientific notation. However, this makes it very difficult to add numbers that are expressed in

different powers of 10. So in the electrical trade, a modified version of scientific notation called *engineering notation* is used.

Engineering notation uses only those powers of 10 with an exponent that is a multiple of three (e.g., 10^{-9} , 10^{-6} , 10^{-3} , 10^3 , 10^6).

Each one of these engineering metric notational values is associated with a prefix. Instead of writing a number with a large power of 10, a metric prefix that represents the multiplier is placed ahead of the *unit*.

For example, 25 000 volts can be written as 25×10^3 volts, which can then be written as 25 kilovolts or 25 kV. The *kilo* represents 10^3 .

It is important that you learn these prefixes and how to convert from one to the other.

Table 1: Common unit prefixes

P	pico	10^{-12}
N	nano	10^{-9}
μ	micro	10^{-6}
m	milli	10^{-3}
← No prefix →		$10^0 = 1$
k	kilo	10^3
M	mega	10^6
G	giga	10^9

Converting between metric prefixes

The easiest way to learn this is to work through some examples step by step. Three examples follow:

Example 1

Express 2500 volts in kilovolts.

Step 1: Express the problem as an equation with the unit you are going from on the left, and the unit you are going to on the right.

$$2500 \text{ V} = \text{_____ kV}$$

Step 2: Replace the prefixes with the appropriate powers of 10.

$$2500 \times (10^0 \text{ V}) = \text{ } \times (10^3 \text{ V})$$

Step 3: In Step 2, the power of 10 on the right-hand side is bigger by 10^3 than the power of 10 on the left. If the equation is to remain balanced, the coefficient (in this case 2500) must be *reduced* by the same factor. That is, it must be *divided* by 10^3 .

To divide by 10^3 , move the decimal point of the coefficient three places to the left.

Place the new number (2.5) on the right-hand side of the equation.

$$2500 \times 100 \text{ V} = 2.5 \times 10^3 \text{ V}$$

Step 4: Change the powers of 10 back to the appropriate prefixes.

$$2500 \text{ V} = 2.5 \text{ kV}$$

Example 2

Express 0.057 milliamperes in microamperes.

Step 1: Express the problem as an equation with the unit you are going from on the left, and the unit you are going to on the right.

$$0.057 \text{ mA} = \text{_____} \mu\text{A}$$

Step 2: Replace the prefixes with the appropriate powers of 10.

$$0.057 \times (10^{-3} \text{ A}) = \text{_____} \times (10^{-6} \text{ A})$$

Step 3: In Step 2 the power of 10 has decreased by 10^3 , so if the equation is to remain balanced, the coefficient (in this case 0.057) must be increased by the same factor. That is, it must be multiplied by 10^3 .

To multiply by 10^3 , move the decimal point three places to the right.

$$0.057 \times 10^{-3} \text{ A} = 57 \times 10^{-6} \text{ A}$$

Step 4: Change the powers of 10 back to the appropriate prefixes.

$$0.057 \text{ mA} = 57 \mu\text{A}$$

Example 3

Express 5600 milliohms in kilohms.

Step 1: Express the problem as an equation with the unit you are going from on the left, and the unit you are going to on the right.

$$5600 \text{ m}\Omega = \text{_____} \text{ k}\Omega$$

Step 2: Replace the prefixes with the appropriate powers of 10.

$$5600 \times 10^{-3} \Omega = \text{_____} 10^3 \Omega$$

Step 3: In Step 2, the power of 10 has increased by 10^6 , so if the equation is to remain balanced, the coefficient (in this case 5600) must be reduced by the same factor (divided by 10^6).

To divide by 10^6 , move the decimal point six places to the left.

$$5600 \times 10^{-3} \Omega = \text{_____} 0.0056 \times 10^3 \Omega$$

Step 4: Change the powers of 10 back to the appropriate prefixes.

$$5600 \text{ m}\Omega = 0.0056 \text{ k}\Omega$$

When expressing an electrical value, it is customary to choose the metric prefix so that the coefficient falls between the values of 1 and 999. For example, because the coefficients 2400 and 0.056 do not fall within the range of 1 to 999:

- the value 2400 volts is expressed as 2.4 kilovolts
- the value 0.056 amperes is expressed as 56 milliamperes.

Motor efficiencies

Motors are rated in horsepower (except for tiny motors used in toys, computers drives and the likes). **One horsepower is equal to 746 watts.** Horsepower refers to the amount of work the motor delivers on the shaft, which is the motor's output. The amount of power a motor draws from the source is the motor's input. No motor is 100 percent efficient.

- The efficiency of a motor is the ratio of the watts out to the watts in operating at rated load.

Efficiency is expressed as a percentage in the following form:

$$\% \text{ efficiency} = \frac{\text{output watts}}{\text{input watts}} \times 100$$

Example 1

A motor operating at rated load is drawing 2400 watts from the supply and delivers 2000 watts on the shaft. Determine the efficiency of the motor.

$$\% \text{ efficiency} = \frac{2000 \text{ W}}{2400 \text{ W}} \times 100 \quad \% \text{ efficiency} = 0.833 \times 100 = 83.3\%$$

Example 2

A 10 HP (nameplate rating) motor is operating at an efficiency of 75%. Determine the input watts drawn by the motor.

$$10 \times 746 \text{ W} = 7460 \text{ watts output}$$

$$\frac{7460}{.75} = 9947 \text{ watts input}$$

Example 3

A 240 volt motor draws 20 A and is delivering 3730 watts at rated load. Determine the HP the motor is delivering on the shaft.

$$\text{Input watts} = 20 \text{ A} \times 240 \text{ V} = 4800 \text{ W}$$

$$\% \text{ efficiency} = \frac{3730 \text{ W}}{4800 \text{ W}} \times 100 \quad \% \text{ efficiency} = 0.777 \times 100 = 77.7\%$$

$$\text{Motor HP} = \frac{3730 \text{ W}}{746 \text{ W}} = 5 \text{ HP}$$



Now do Self-Test 5 and check your answers.

Self-Test 5

1. If it requires 120 volts to push current through a light bulb at the rate of 2.5 amperes, what is the power rating of the light bulb?

2. What is the resistance of the filament in the light bulb in Question 1?

3. If a heater connected to a 240 V source of electromotive force draws a current of 3.125 amperes, what is the resistance of the heater?

4. What is the power rating of the heater in Question 3?

5. If the voltage applied to a circuit increases, the current through the circuit _____.

6. If the resistance of a circuit decreases, the current flowing through the circuit _____.

7. If the resistance of a circuit decreases, the power dissipated by the circuit _____.

8. If the voltage applied to a circuit doubles, the power dissipated by the circuit _____ by _____ times.

9. State Ohm's law in words rather than in symbols.

10. State Watt's law in words rather than in symbols.

11. Express 13 800 volts as kilovolts.

12. Express 0.0034 milliamps as microamperes.

13. Express 500 000 volts as megavolts.

14. Express 18.2 microamperes as amperes.

15. Express 470 kilohms as ohms.

16. Express 27 000 000 microhms as kilohms.

17. How many kilowatts are equal to 1500 watts?

18. Express 1500 watts as milliwatts.

19. A certain heater draws 12.5 amperes when a voltage of 240 volts is applied across it. What is the power rating of this heater in kilowatts?

20. A voltage of 5 volts is applied across a resistor of 25 kilohms. How many microamperes of current will flow through the resistor?

21. A motor draws 6000 watts from the supply and delivers 4200 watts on the shaft. Determine the efficiency of the motor.

22. A 120 volt motor draws 66.61 amps from the supply and is 70% efficient. Determine the output watts and HP of the motor.
-

23. A 240 volt, 10 HP DC motor is 80% efficient. Determine the input watts drawn by the motor and how many amps the motor is drawing from the supply.
-

24. A motor delivers 14 920 watts on the shaft and is 75% efficient. Determine the input watts drawn by the motor and HP delivered by the motor on the shaft.
-

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

Learning Task 6:

Describe the relationship between electrical power and energy

People often refer to energy and power as the same thing. As an electrical worker, you must understand that they are not the same thing, although they are related.

Energy is the ability to do work

Work, in the purely mechanical sense, is done when an applied force moves an object through a distance in the direction of the applied force. It is defined as *force times distance*. When work is done on an object, the object is given energy equal to the work done on it. The object can then transfer that energy to another object by doing work on it. The symbol for energy is W, which is also the symbol for work.

For example, if a force is applied to a volume of water to lift it and place it up behind a dam, that volume of water has gained energy. (In real life, the energy used to move the water up behind the dam comes from the sun.) If this water is allowed to drop onto a turbine, the energy possessed by the water can be transferred to the turbine. The water has done work on the turbine. Now the turbine has mechanical energy and can do work on something else.

Power is the rate of doing work

If more water is allowed to fall on the turbine in a given period, energy can be transferred to the water wheel faster. To use another example, a person who can chop wood at the rate of 30 logs per hour has twice the power of a person who can chop only 15 logs in the same time. If the second person worked for two hours, that person could also chop 30 logs (15×2). Both people would have expended the same total energy.

If energy is equal to the work done and power is equal to work done divided by time, then energy must equal power times time.

$$\text{Power} = \text{work} \div \text{time}$$

$$= \text{energy} \div \text{time}$$

$$\text{Energy} = \text{power} \times \text{time}$$

In electrical units, power is equal to volts times amperes, so energy is equal to volts times amperes times time. The electrical supply authority charges its customers for energy, not power. The meters that the supply authority uses to measure the energy consumption of its customers are kilowatt-hour meters. The unit of energy is the kilowatt hour, the unit of power is the kilowatt and the unit of time is the hour.

Example 1

If a household dryer draws 25 amperes from the supply at a voltage of 240 volts for a period of $\frac{1}{2}$ hour, what power is the dryer operating at and what is the energy required to dry the clothes?

$$\begin{aligned}P &= E \times I \\&= 240 \text{ V} \times 25 \text{ A} \\&= 6000 \text{ W} \\&= 6 \text{ kW}\end{aligned}$$

$$\begin{aligned}W &= P \times t \\&= 6 \text{ kW} \times \frac{1}{2} \text{ h} \\&= 3 \text{ kWh}\end{aligned}$$

Example 2

If the supply authority charges \$.07 per kilowatt hour, how much does it cost to dry the clothes?

$$\begin{aligned}\text{Cost} &= 3 \text{ kWh} \times \$.07/\text{kWh} \\&= \$.21\end{aligned}$$

Example 3

If the supply authority charges \$.07 per kilowatt hour of energy, what does it cost to leave a 40 watt porch light on for 24 hours?

$$\begin{aligned}W &= P \times t \\&= 0.04 \text{ kW} \times 24 \text{ h} \\&= 0.96 \text{ kWh}\end{aligned}$$

$$\begin{aligned}\text{Cost} &= 0.96 \text{ kWh} \times \$.07/\text{kWh} \\&= \$.0672\end{aligned}$$

Example 4

A 240 V water heater draws 18 A from the source for a period of 25 minutes. Answer the following questions:

1. What is the power rating of the water heater?

$$\begin{aligned}P &= E \times I \\&= 240 \text{ V} \times 18 \text{ A} \\&= 4.32 \text{ kW}\end{aligned}$$

2. What was the energy consumption of the water heater during this time?

$$\begin{aligned}W &= P \times t \\&= 4.32 \text{ kW} \times (25 \div 60) \text{ h} \\&= 1.8 \text{ kWh}\end{aligned}$$

3. At the rate of \$.07/kW/h what would this cost?

$$\begin{aligned}\text{Cost} &= 1.8 \text{ kW/h} \times \$.07/\text{kW/h} \\ &= \$.126\end{aligned}$$



Now do Self-Test 6 and check your answers.

Self-Test 6

1. The product of emf, current and time is _____ .
2. The product of emf and current is _____ .
3. The product of power and time is _____ .
4. How many kilowatt hours of energy does it require to operate a 1200 watt hair dryer for 10 minutes?

5. If the supply authority charges \$.07 per kilowatt hour, what does it cost to operate the hair dryer in Question 4?

6. If a 25 kW electric furnace operates for 3 hours in a 24-hour period, and the supply authority charges \$.07/kW/h, what does it cost each day to operate the furnace?

7. If an electric clothes dryer draws 30 A at 240 V and is operated for 45 minutes, what is the kW/h consumption?

8. What is the power rating of the dryer in Question 7?

9. A 1500 W/240 V baseboard heater is operated for 15 minutes and a 1200 W/120 V baseboard heater is operated for 30 minutes. What is the combined kW/h consumption of the two heaters?

10. At \$.07/kW/h, what is the cost of operating the two heaters in Question 9?

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

Learning Task 7:

Identify common drawings for electric circuits

The old saying that a picture is worth a thousand words is very appropriate for the electrical trade. Most information conveyed to the electrical tradesperson through drawings is virtually impossible to convey verbally or in writing. For this reason, you must learn how to recognize and interpret the diagrams commonly used in the electrical trades.

In this Learning Task you will be introduced to four main types of electrical drawings: pictorial, block, wiring and schematic.

Pictorial diagrams

Pictorial diagrams are the easiest to understand. They are often used to instruct people who have limited formal electrical training, yet wish to understand the workings of electric circuits. Instruction manuals for stereo and video equipment commonly use pictorial circuit drawings. Such drawings are also used by the manufacturers of do-it-yourself kits for the hobbyist. The circuit in Figure 1 is in pictorial form.

As pictorial diagrams are usually designed for untrained people, the drawings often have these characteristics:

- Components are drawn as they really appear.
- Components in the diagram are located relative to their actual circuit positions.
- Wire colours are indicated by name.
- Diagrams have a three-dimensional effect.

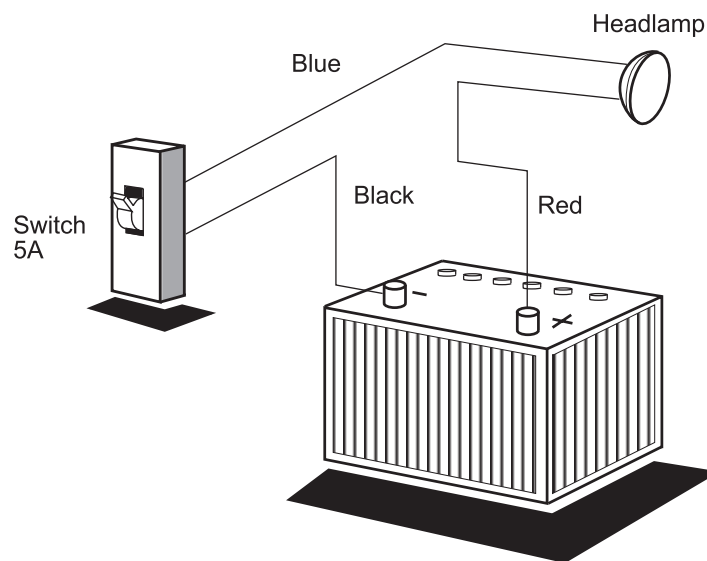


Figure 1—Pictorial diagram of a simple circuit

Block diagrams and one-line diagrams

A *block diagram* is a type of flow chart that indicates the relationship between individual circuit components or groups of components within the same housing. These diagrams often show a logical sequence of events. In these diagrams, the components of the circuit are drawn in the form of blocks, and their relationship to each other is indicated by appropriately connected lines. Figure 2 shows a block diagram.



Figure 2—Block diagram

The difference between a block diagram and a one-line diagram is that the *one-line diagram* uses symbols for the components and the block diagram uses only blocks. One-line diagrams are also called *single-line diagrams* or *riser diagrams*. Figure 3 shows a one-line diagram.

One-line diagrams are often used to illustrate the major equipment in an electrical distribution system, as in Figure 4a and Figure 4b. They are usually the first drawings made in the design of a large project, and their intent is to represent a clear picture of the main in-line components in the system or circuit.

One-line diagrams commonly show the highest voltage (or line side) components at the top of the drawing, and work their way down the page to progressively lower voltage (or load) components of a distribution or feeder circuit.

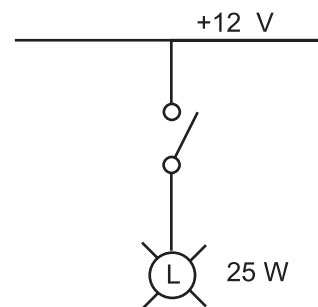


Figure 3—One-line diagram

The one-line diagram has several distinguishing characteristics:

- The components are labelled to show their name, type and sometimes even their catalogue number.
- They are not used to show the actual circuit position of the components.
- The single lines do not show the return path for the circuit. To help understand the circuit, you can think of the line as being the conduit that contains the conductors.

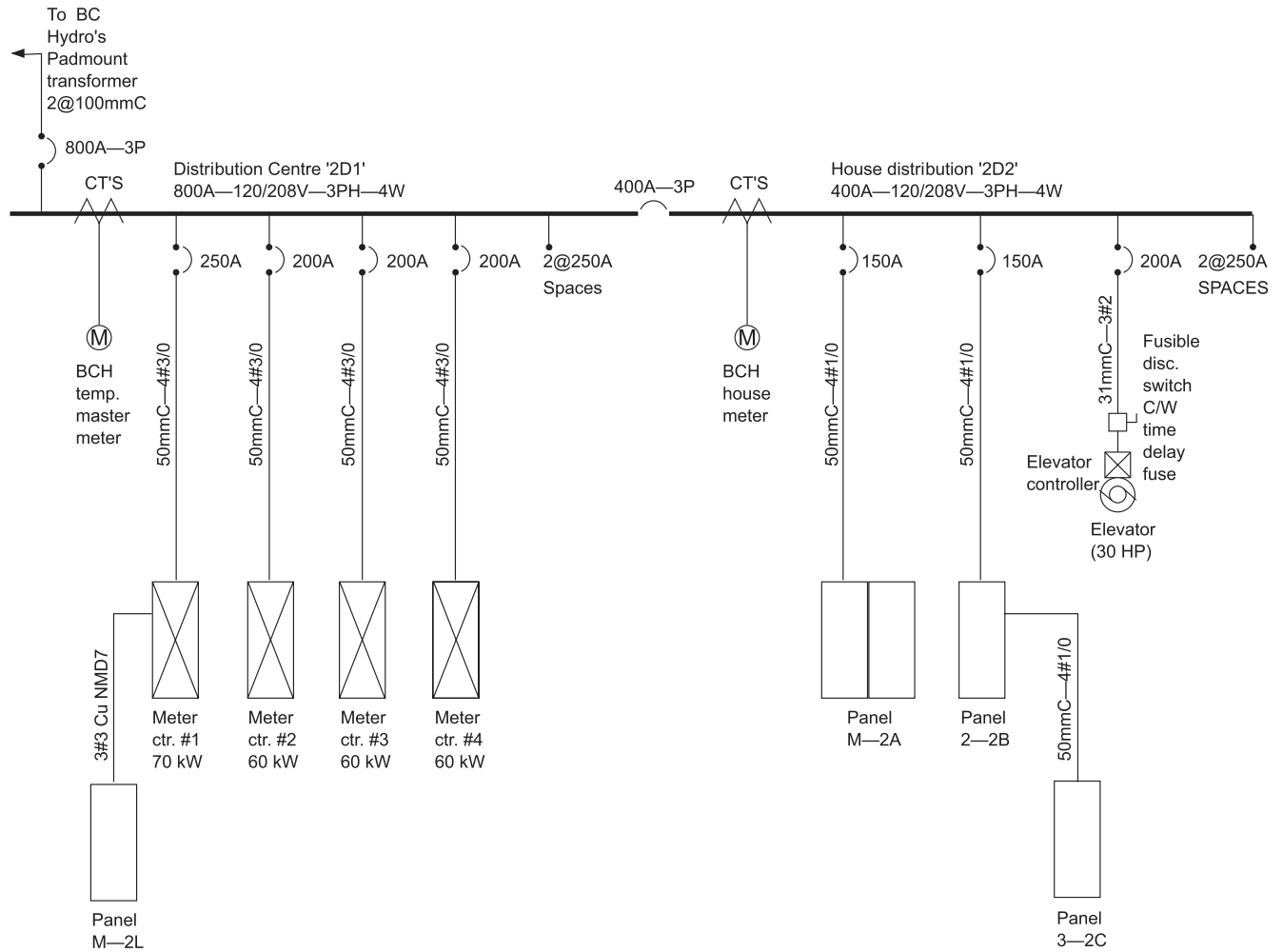


Figure 4a—One-line diagram

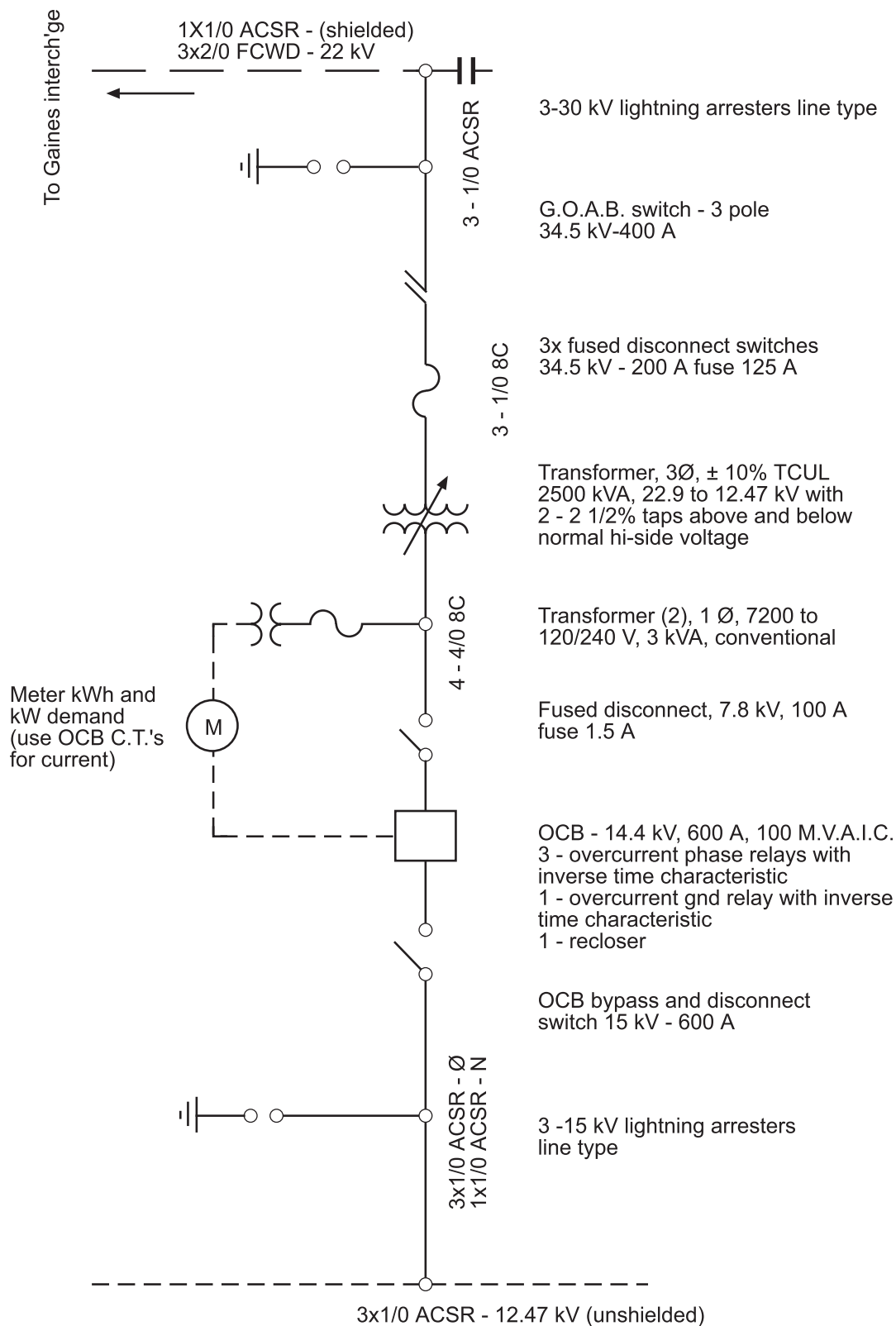


Figure 4b—One-line diagram

Wiring diagrams

A *wiring diagram* shows, as clearly as possible, the actual location of all the components of a circuit. It is essentially a pictorial diagram drawn without using three-dimensional component representations. The components are usually shown in symbol form.

Wiring diagrams are circuit maps. They are very useful for the initial wiring of a circuit and for tracing wires when troubleshooting. Wiring diagrams show exactly how and where the wires are connected and run between devices. Figure 5 is a wiring diagram for starting and stopping two motors, complete with pilot light indication.

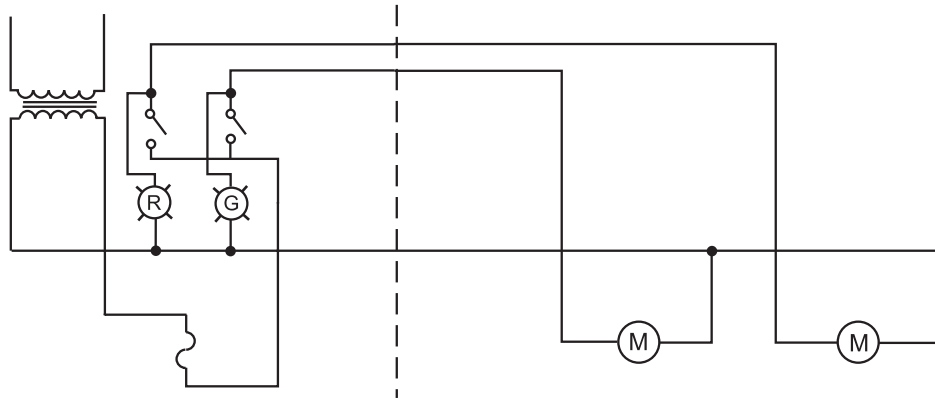


Figure 5—Wiring diagram

Notice that all the wires run either horizontally or vertically to make the diagram neater and easier to follow. When two wires cross, a dot is used to indicate that the wires are connected. If a dot is not shown, the wires cross each other but do not connect electrically.

Schematic diagrams

The *schematic diagram* shows the electrical relationship between the components of a circuit, but in order to be simple, it gives no indication of the physical relationship between components. Schematic diagrams are intended to be used to gain an understanding of how the circuit works and what it is supposed to do.

The schematic diagram in Figure 6 shows the same circuit as Figure 5. It is much easier to follow the flow of current through the circuit in Figure 6 than it is to follow the flow of current through Figure 5. The schematic diagram emphasizes how the circuit works rather than how it looks.

The type of schematic diagram shown in Figure 6 is called a *ladder diagram*. In a ladder diagram, the two vertical lines on either side of the diagram represent the source of the power. The wires connected between the source conductors form the rungs of the ladder.

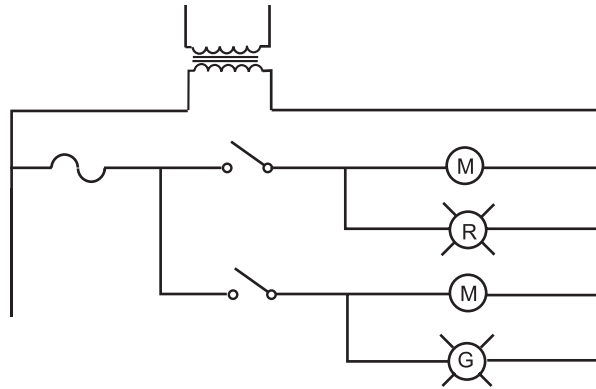


Figure 6—Schematic diagram

Figures 7 to 10 are examples of the same circuit represented by pictorial, block, wiring and schematic diagrams.

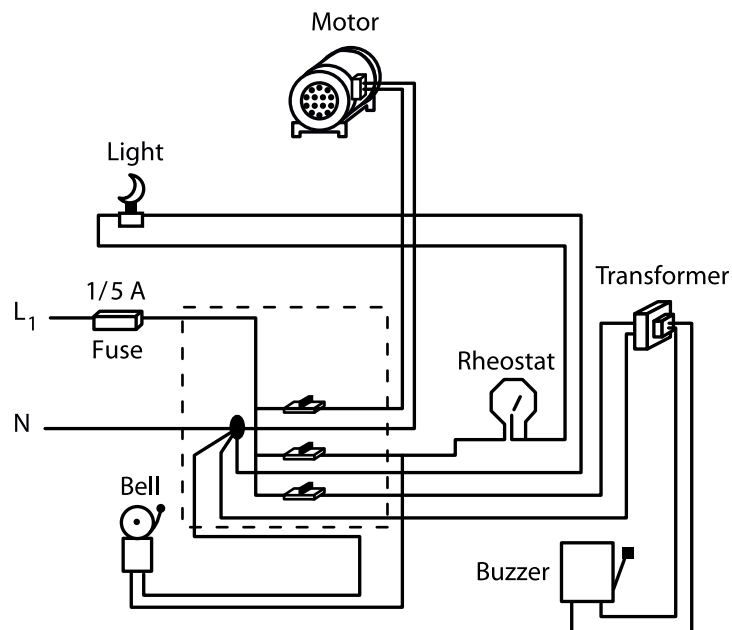


Figure 7—Pictorial diagram

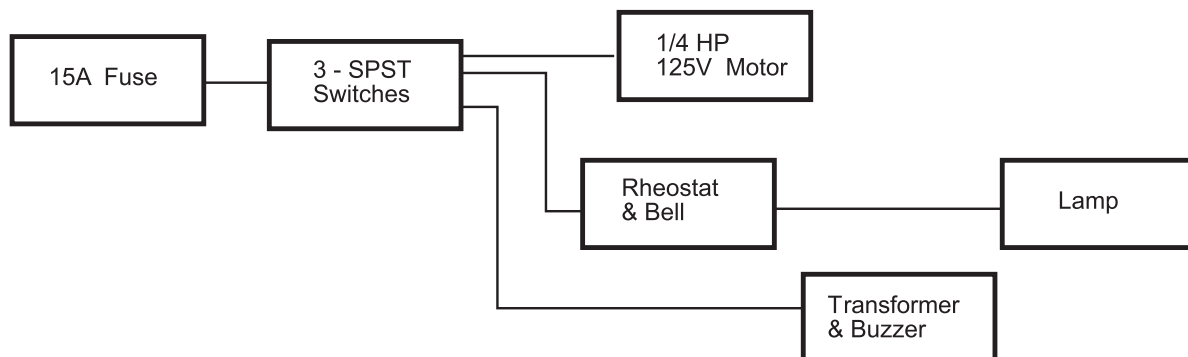


Figure 8—Block diagram

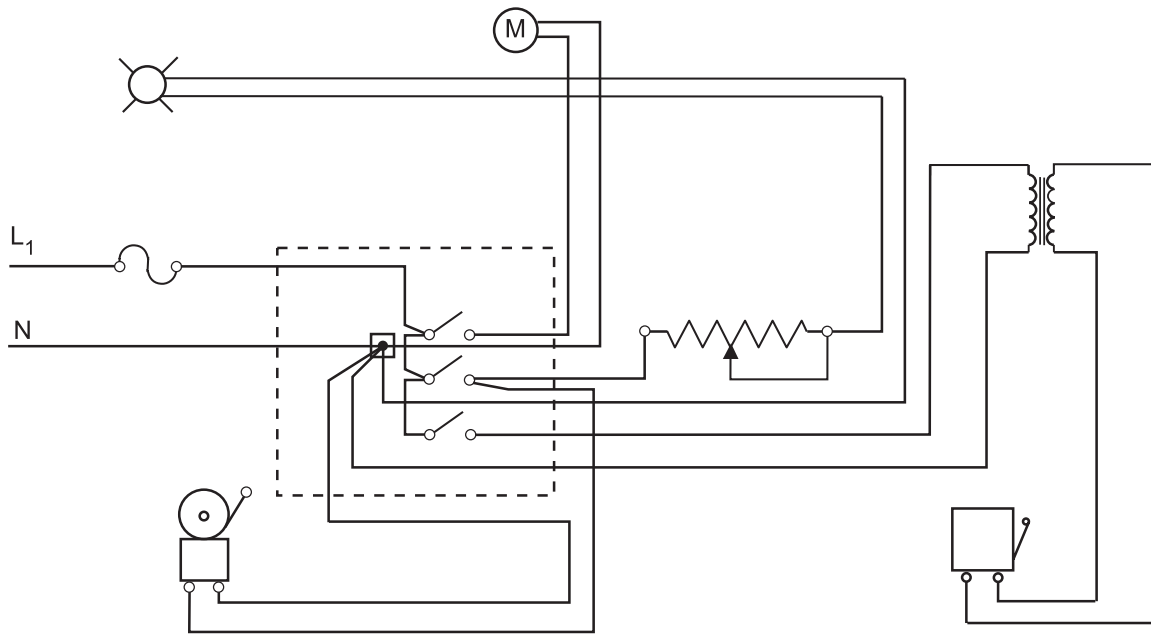


Figure 9—Wiring diagram

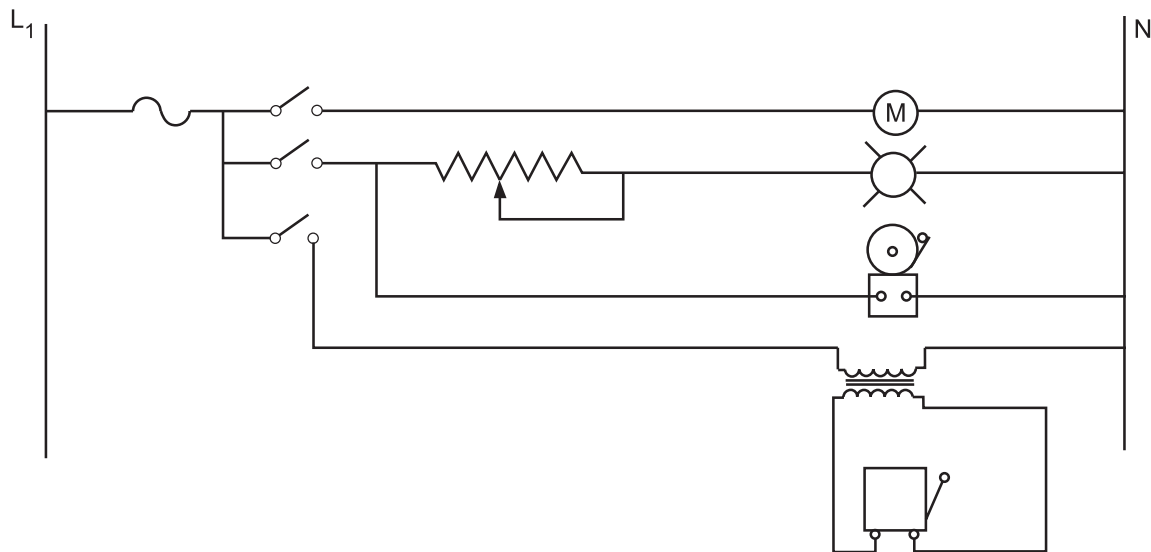


Figure 10—Schematic diagram



Now do Self-Test 7 and check your answers.

Self-Test 7

1. The diagram that is easiest to understand for a person with little knowledge of electricity is a _____ diagram.
2. The type of schematic diagram that shows the power source as two vertical lines on either side of the drawing is called a _____ diagram.
3. The main difference between a block diagram and a one-line diagram is that to represent the components, a block diagram uses _____ and a one-line diagram uses _____.
4. Schematic diagrams do not show the _____ relationship between components.
5. The type of diagrams in which components are shown as they really appear are _____ diagrams.
6. The diagram that is a type of flow chart is the _____ diagram.
7. The type of diagram that is a circuit map is a _____ diagram.
8. The type of diagram that shows a three-dimensional view of the component is the _____ diagram.
9. The diagram that does not show the individual conductors is the _____ diagram.

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

Learning Task 8:

Describe the operation of electric circuits

The term *circuit* refers to a circular journey or loop. In the case of an electric circuit, it is the journey or loop travelled by the electrons. Three basic conditions must exist to have a complete circuit so that electrons may flow. These are as follows:

- The *source*, which is the device that changes other forms of energy into electrical energy. It is the part of the circuit that provides the electromotive force that pushes the electrons through the circuit. Some examples of sources are batteries, generators, solar cells and thermocouples.
- The *load*, which is the device that changes electrical energy into other forms of energy. It is the part of the circuit that performs useful work. Some examples of loads are lights, heaters, motors, radios and refrigerators.
- The *conductors*, which complete the path or circuit for the electrons to follow. Some examples of conductors are wires and busbars.

Before current will flow, the three pieces of the circuit listed above must be connected so that they provide a complete path for the current flow. In Figure 1, electrons are pushed from the negative terminal of the source, through the wires to the load. They give up most of their energy as they pass through the load, then pass through the return wires to the positive terminal of the source. Inside the source, the electrons are given more energy as they are again forced toward the negative terminal.

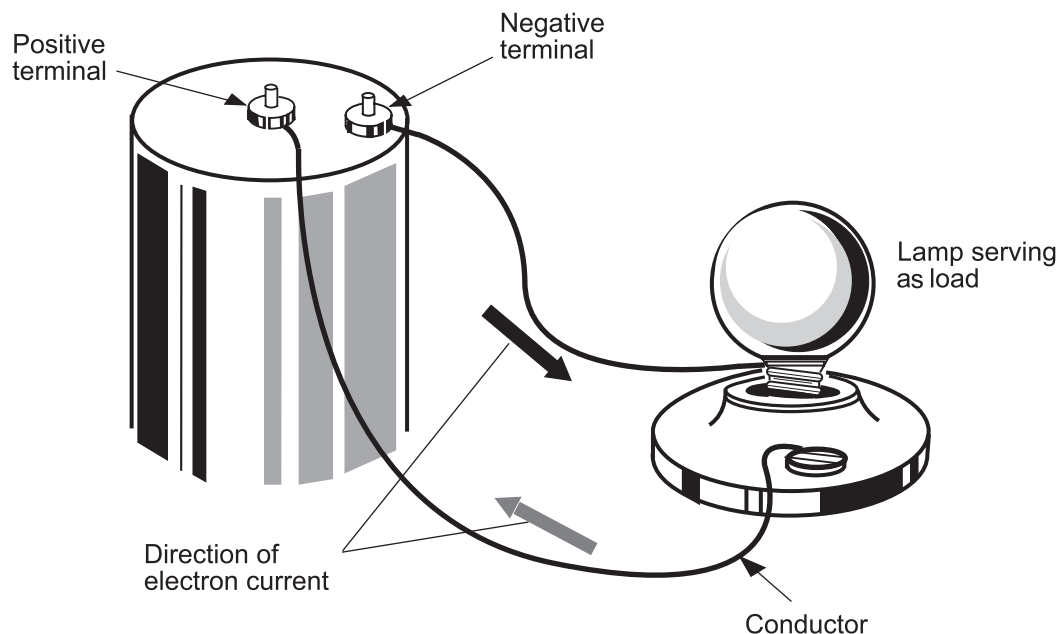


Figure 1—A complete circuit

Electrons can be thought of as a tanker truck delivering fuel to a service station. In this case, the source of fuel is the oil refinery, the highways are the conductors, the service station is the load and the tanker truck represents the electrons.

- At the refinery, the tanker is given energy as the tanks are filled.
- The tanks that supply fuel to the engine are also filled.
- On the way to the service station, the tanker gives up some fuel (energy) to drive the engine.
- At the service station, the tanker gives up most of its energy as it drains its tanks.
- On the way back to the refinery, the tanker gives up the rest of its energy to drive the engine.
- At the refinery, the tanker is given new energy as it is refuelled.

If any one of the three basic conditions described on the previous page is missing, the circuit is incomplete and no current flows. If there is a break in the circuit or any one of the conditions is not met, the circuit is referred to as an *open circuit*. When a circuit is open, it means there is an opening in the path somewhere and the current cannot flow.

When all three basic conditions are met, the circuit is referred to as a *closed circuit*. See Figure 2. In a closed circuit, electrons can flow.

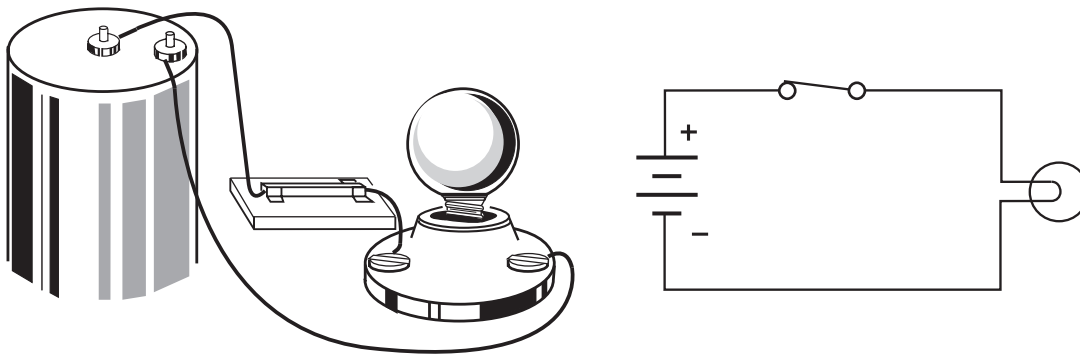


Figure 2—A closed circuit

If, for some reason, a wire is accidentally connected across the terminals of the source as shown in Figure 3, it provides a shortcut with less resistance to current flow. Because the electrons tend to take the path of least resistance, *most* of the electrons will take the shortcut. This is referred to as a *short circuit*.

A short circuit is defined as a parallel path of low resistance.

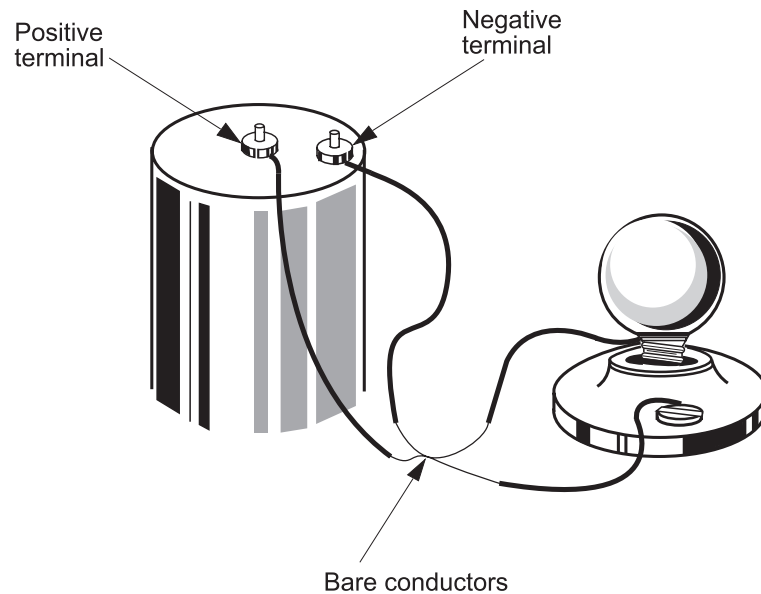


Figure 3—A short circuit

Other components in a circuit

A complete circuit containing a source, a load and the conductors functions perfectly well, but it does not allow control of the load (such as on/off, fast/slow). Also, if a short circuit occurs, the components are not protected. In practice, circuits usually include devices such as switches and fuses to control the load and protect against currents that are too large.

Switches

Switches control the flow of current through the load by opening the circuit and disconnecting the load from the source. A switch can be placed anywhere in the circuit. Figure 4 shows an electric circuit with an open switch. When the switch is open it opens the circuit and the lamp is dark or off. When the switch is closed it closes the circuit and the lamp is bright or on.

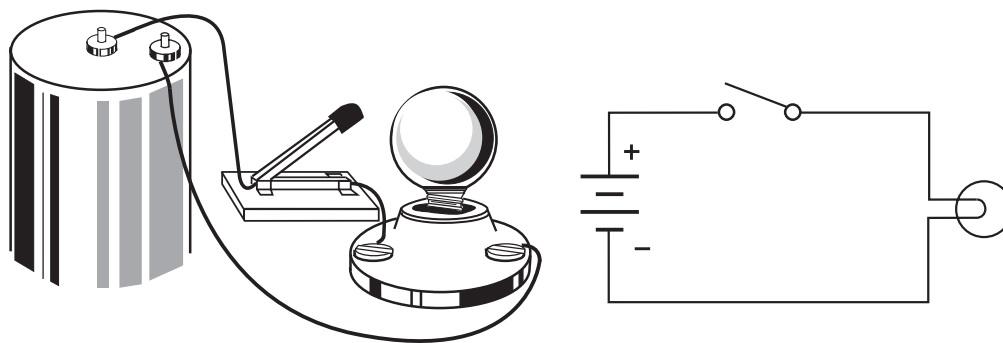


Figure 4—An open circuit

Fuses and circuit breakers

Fuses or circuit breakers are added to circuits to protect the components from having too much current flow through them. Too much current can cause damage from excess heat, or

mechanical damage due to strong magnetic fields. This can cause fire or explosive forces. Fuses or circuit breakers are placed in the circuit so that all of the current flowing in the circuit must also flow through the fuse or breaker. These devices measure the current and, if it is too large, they open the circuit to disconnect the load from the source. Figure 5 shows a circuit with a fuse inserted to protect against excessive current. A circuit breaker could be used instead of the fuse in this circuit.

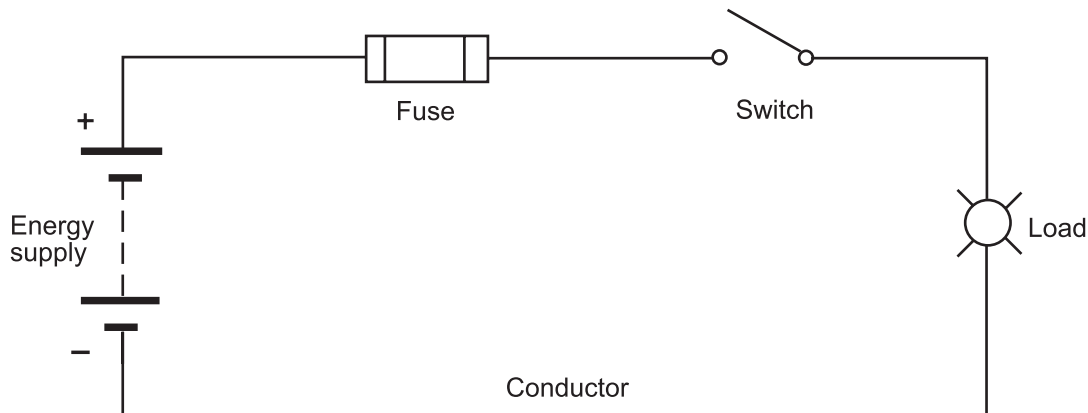


Figure 5—A fused circuit

Polarity and direction of current flow

Earlier you learned about the term *polarity*. It referred to the charge at one point with respect to another. In electric circuits we often refer to the polarity between different points in the circuit. This is important for connecting the leads of polarity-dependent devices such as some meters and motors. Polarity is also important for determining the direction of current flow. In Figure 6 the current leaves the source at the negative terminal, travels around the circuit in a clockwise direction and re-enters the source at the positive terminal.

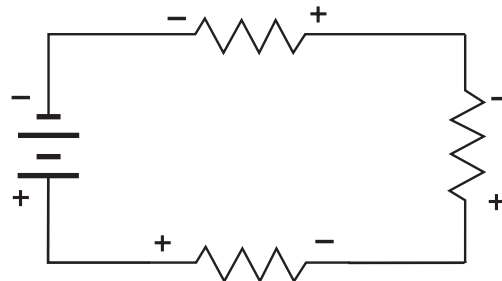


Figure 6—Polarity

It is important to notice that current flows through *loads* from negative to positive, and current flows through *sources* from positive to negative. Remembering these two facts can be very useful in analyzing what a circuit is supposed to do. A more precise way of stating this is that outside the source, current flows from negative to positive, but inside the source current flows from positive to negative.

Direct current and alternating current

So far all the energy supplies you have learned about have polarities that do not change, and electrons flow through the circuit in only one direction. This type of supply and current flow is referred to as *direct current*. Direct current (DC) is current that flows in the same direction all of the time. Batteries, thermocouples, photovoltaic cells and DC generators are all sources of direct current.

Alternating current (AC) changes its direction continuously and at regular intervals. This type of current is produced by alternators. The alternating current used in our homes is a *60-cycle alternating current*, which means that the polarity of the supply changes 120 times per second, producing 60 complete cycles each second.

It is important that you gain an understanding of direct current before starting to study the more complex alternating current.



Now do Self-Test 8 and check your answers.

Self-Test 8

1. A device that changes electrical energy into other forms of energy is referred to as a _____ .
2. A parallel path of low resistance is the definition of a _____ .
3. The two main types of damage that are likely to occur because of excessively high current are _____ and _____ .
4. Current flows through a load from _____ to _____ .
5. The term that refers to the charge at one point with respect to another point is _____ .
6. A fuse or circuit breaker protects a circuit from excessive current by _____ the circuit when too much current flows through it.
7. When a switch is in the open position, is it on or off? _____
8. Current flows through the source from _____ to _____ .
9. The three necessary components of a circuit are the _____ , _____ and _____ .
10. To stop the load, the switch must be _____ .

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

Learning Task 9:

Calculate values of voltage, current, resistance and power in electric circuits

You already know Ohm's law and Watt's law. Stated in words and mathematically, they are:

Ohm's law

The current in an electric circuit is directly proportional to the applied voltage and inversely proportional to the resistance of the circuit.

$$I = E \div R$$

Watt's law

The power transformed in an electric circuit is equal to the product of the applied voltage times the circuit current.

$$P = E \times I$$

You learned earlier that it is possible to generate 10 more equations from these two by using transposition and substitution. With these equations, if you have any two of the electrical quantities, you are able to calculate the other two. It is very important to be able to do this, because it is not always practical or even possible to measure all four of these quantities.

For example, the resistance of a 120 V/100 W light bulb is 144 Ω when it is hot and only about 10 Ω when it is cold. For the light bulb to be hot, the power must be on, but to use an ohmmeter, the power must be off, so it is not possible to measure the hot resistance of the light bulb. It is possible, however, to measure the voltage and current when the light bulb is hot and use Ohm's law to calculate the hot resistance.

Power dissipation in a resistive device

Loads are devices that convert electrical energy to other forms of energy. Purely resistive devices convert energy mainly to heat. Sometimes a small portion of the energy is converted to light as well, depending on how hot the device gets.

As electrons travel through a resistance, they bump into molecules of the material. They give up some of their energy to the molecules. This energy increases the motion of the molecules, which causes the resistive device to become warmer.

If the rate of electron flow (current) is increased, the number of collisions also increases. This means the rate at which energy is transferred from the electrons to the molecules also increases, and the resistive device becomes even warmer.

Power is the rate of doing work or the rate of energy transfer. It follows that if the current increases, causing an increase in the rate of energy transfer, then the power must also increase. Voltage is a measure of the amount of energy possessed by an electron. It follows that, as voltage increases, each electron has more energy to transfer and the power increases. This

means that power is directly proportional to both the voltage and the current. Power increases if either or both of these two quantities increase.

From Ohm's law you know that the current in a circuit is directly proportional to the applied voltage. This means that if the voltage doubles, the current also doubles. The voltage doubling causes the power to double, and the current doubling causes a further doubling of the power. The power in this case will increase by four times.

This can be stated in words and mathematically as follows:

Power is directly proportional to the square of the voltage.

$$P = \frac{E^2}{R}$$

The power is also directly proportional to the square of the current.

$$P = I^2 \times R$$

Power loss in conductors

It would be nice if we could develop conductors that have no resistance (called superconductors), but so far, under normal conditions, this is not the case. Notice that both the power equations above include resistance. Whenever a current passes through a conductor with resistance, some electrical energy must be converted to heat. This power loss is often referred to as the I^2R loss (pronounced *I squared R loss*) of the conductor. You can see that this comes from the equation above.

This heating of the conductor is considered wasteful and attempts are made to minimize it by reducing the resistance of the conductors as much as possible. As an electrical worker you will have to take this heating into account and design your circuits to reduce energy waste as much as possible.

If the conductors feeding the energy to your house have a resistance of 30 mΩ and carry a current of 80 A, what is the I^2R loss in these conductors?

$$\begin{aligned} P &= I^2 R \\ &= 80^2 \text{ A} \times 0.03 \text{ } \Omega \\ &= 192 \text{ W} \end{aligned}$$

Now consider the total power loss for all the other houses in British Columbia. The power authority must generate this wasted energy at its generating stations. Think of how many generating stations in the world could be eliminated if this power loss could be reduced. Think of what that would mean to the reduction of pollution.

Solving problems about electric circuits

Electrical circuit problems are solved by applying Ohm's law and Watt's law, and by using the requirements for a complete circuit. This includes using the 12 related equations that you must be able to derive from the two laws by transposition and substitution. Here are a few examples of solving electrical application problems.

Example 1: What voltage is required to force current through a $38.4\ \Omega$ heater at a rate of 6.25 A ?

$$\begin{aligned} E &= I \times R \\ &= 6.25\text{ A} \times 38.4\ \Omega \\ &= 240\text{ V} \end{aligned}$$

Example 2: If a voltage of 120 V applied across a heater produces heat at the rate of 1500 W , what current is flowing through the heater?

$$\begin{aligned} I &= \frac{P}{E} \\ &= \frac{1500\text{ W}}{120\text{ V}} \\ &= 12.5\text{ A} \end{aligned}$$

Example 3: What is the resistance of the heater in Example 2?

$$\begin{aligned} R &= \frac{E^2}{P} \\ &= \frac{120\text{ V}^2}{1500\text{ W}} \\ &= 9.6\ \Omega \end{aligned}$$

Example 4: What power is dissipated when 417 mA of current flows through a $576\ \Omega$ light bulb?

First, adjust the units: $417\text{ mA} = 0.417\text{ A}$

$$\begin{aligned} P &= I^2 \times R \\ &= 0.417^2 \text{ A} \times 576\ \Omega \\ &= 100\text{ W} \end{aligned}$$

Example 5: What is the voltage rating of the light bulb in Example 4?

$$\begin{aligned} E &= I \times R \\ &= 0.417\text{ A} \times 576\ \Omega \\ &= 240\text{ V} \end{aligned}$$



Now do Self-Test 9 and check your answers.

Self-Test 9

1. The term I^2R loss refers to a _____ loss.
2. If the voltage applied across a purely resistive device is made three times larger, the power dissipated by that device is multiplied by _____.
3. If a current of 6.25 amperes flows through a stove element when 120 volts is applied across the element, what is the power dissipated by the element?

4. What is the resistance of the stove element in Question 3?

5. If 240 volts are applied across the stove element in Question 3, what power would be dissipated by it?

6. What current must flow through a $120\ \Omega$ automotive block heater to produce heat at the rate of 100 W? (Give the answer in milliamps.)

7. What voltage would have to be applied across the heater in Question 6 to cause the 100 W of heat to be dissipated?

8. What is the resistance of a 1200 W/120 V hair dryer?

9. What current is drawn from the source by a 1500 W/120 V electric fry pan?

10. If the voltage applied to an electric circuit is doubled, what happens to the current flowing through that circuit?

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

Learning Task 10:

Use meters for simple circuit measurements

Electricity is something that cannot be seen. However, it is possible to see the effects of electricity. Even when you see lightning, you are not seeing electricity, but rather the release of electrical energy in the form of light. When an electric circuit is not operating correctly, it is very difficult to look at the circuit and discover what is wrong.

Meters are used to measure the effects of electricity. As the electrical quantities vary, so does the effect they have on the meter. Some of these effects are very small, so most meters must be built with very delicate operating mechanisms. Meters are precision instruments that can be damaged easily. Most of them are not constructed to take a lot of abuse. You must take great care when storing, handling and using these electrical devices.

Handling and storage precautions

You must take several precautions when handling and storing electrical meters. They can be affected seriously by their environment.

Shock and vibration

Electrical measuring instruments contain delicate parts supported in guides and jewelled bearings. These parts often include moving coils. Moving coil instruments are particularly susceptible to vibration and sudden impact. Dropping such a tool will, of course, do damage, but even a violent shake can cause irreparable harm. A sharp rap against a workbench can bend the pointer, which will then need adjusting by an instrument technician.

Some instruments have clamps that lock their movements in place while the devices are being shipped or stored. Wheatstone bridges and clamp-on ammeters are commonly made with such a feature. If the meter you are using has such a built-in holding device, be sure to use it to retain the moving parts when you transport or store it. You must remember to release the mechanism before you use the instrument to take measurements.

Temperature, humidity and dust

Like most delicate instruments, electrical measuring instruments are calibrated to be most accurate under ideal conditions. These instruments are influenced by extreme temperatures and humidity.

Although it is impossible to dictate where and under what conditions you will work, try to protect your instruments from the weather and dirt. If they become wet, dirty or dusty, dry and clean them as soon as possible.

In industrial plants, store electrical instruments in an area where humidity, temperature and dust are controlled. If such an environment is not available, store electrical instruments in dust-proof containers with a small package of absorbent silica gel to keep them dry.

Magnetic fields

Galvanometer-based meter movements contain a permanent magnet. You must avoid placing such instruments near other magnetic fields. A stray magnetic field can cause inaccurate responses from the instrument or even damage to it.

Precautions when using meters

Take these precautions when using electrical measuring instruments:

- Never use a resistance-measuring device on a live circuit. That is, when measuring resistance, make sure the current is OFF. An ohmmeter has its own power source and would be damaged by any other power source. (By contrast, voltmeters, ammeters and wattmeters require the circuit power to be ON when taking measurements.)
- Match the meter to the supply. This means that, if you are working with DC, use a DC meter, and if you are working with AC, use an AC meter.
- On DC voltmeters DC ammeters, and AC or DC wattmeters, always observe the meter polarity when connecting it into the circuit. If the polarity is backward, the meter may be damaged as the pointer tries to deflect the wrong way.
- Check that the meter is oriented correctly to be read. Some meters are meant to be read with the meter sitting up and others are meant to be read with the meter lying down. Failure to use the meter in the proper position results in inaccurate readings. The best way to determine this is to read the owner's manual. Some meters have symbols on the face of the meter. The symbol shown in Figure 1a means the meter should be used lying down, and the symbol shown in Figure 1b means the meter should be used sitting up.



Figure 1—Symbols for positioning meters

- It is important that you read the meter looking straight at the pointer. Looking at the meter from off to either side will introduce an error in reading known as *parallax error*. See Figure 2. To protect against parallax error, some meters are constructed with a small mirror just below the scale markings. If you look straight at this type of meter face, you will not be able to see the reflection of the pointer in the mirror, because it will be directly behind the pointer.

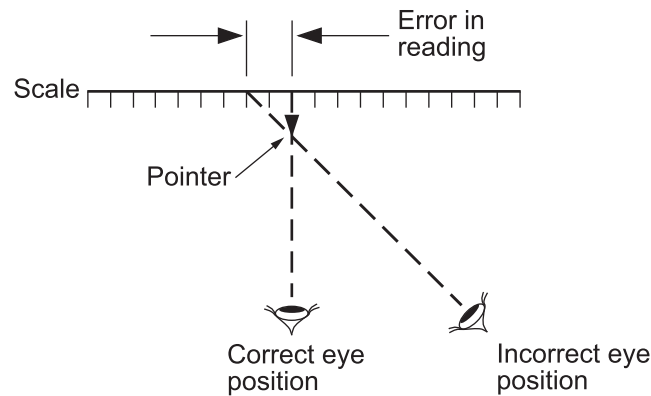


Figure 2—Parallax error

- On multi-range meters, select the range setting that gives the highest pointer deflection on the meter. The meter gives its most accurate readings at full-scale and becomes less accurate the farther away from the top of the scale you get. Estimate the value you expect to read. If you are unsure of the value, start on the meter's highest range and work your way down. Before switching to a lower range, do not forget to check that the measurement will not be too high for that range. Try to select the meter range that will give a reading in the top two-thirds of the scale.
- When finished with a meter, switch it off. If there is no OFF switch-position, switch it to the highest possible range. On a multimeter, switch it to the highest possible AC voltage range.

Voltmeters

The high resistance of a voltmeter means that it draws minimal current from the source.

Voltmeters are used to measure a difference in potential between two points.

- For this reason you must connect the voltmeter *in parallel* with the device across which the voltage is to be measured.
- It is a good practice to test the voltmeter on a known source before and after using it. If, for example, you do not check the meter first and a test lead is faulty, the meter might tell you there is no voltage present when in fact there is. This could be a very dangerous situation.
- Make sure that the meter is on the appropriate range setting and that the proper polarity is observed if it is a DC instrument.

Ammeters

Ammeters are designed with as low a resistance as possible so that they do not add unwanted resistance to the circuit.

- Connect an ammeter *in series* with the circuit so that all of the current must go through it.
- Never connect an ammeter in parallel, as this would form a short circuit.
- Make sure that the meter is on the appropriate range setting and that proper polarity is observed if it is a DC instrument.

Wattmeters

The wattmeter has four test leads. Two are for measuring the current, and two are for measuring the voltage. Recall that the power in a circuit is equal to the product of the voltage and the current. The wattmeter measures the effects of both of these and multiplies the effects together to give the power. You must observe several things when using a wattmeter:

- Connect the voltage coil in parallel with the load. Do not exceed the rating of the voltage coil.
- Connect the current coil in series with the load. Do not exceed the rating of the current coil.
- Do not exceed the power rating of the meter.
- You must observe the polarity of *both* coils. Otherwise the meter pointer will try to deflect down below the zero of the scale and the meter may be damaged.

Ohmmeters

Ohmmeters are used to measure resistance. They have their own source of electromotive force and *must not* be used on live circuits. You must observe several things when using an ohmmeter:

- Never use an ohmmeter on a live circuit.
- Disconnect one end of the device to be measured from the circuit. This prevents the circuit from becoming a parallel path for the current, which would give an incorrect, low reading.
- The scale on most ohmmeters reads backward to other meters. Zero is on the right and infinity is on the left. There is a separate zero adjustment for the ohms scale. This adjustment is used to compensate for the changing state of charge of the internal battery. Every time you change scales on the ohmmeter you must zero the meter again. This is done by shorting the test leads and then turning the adjustment knob.
- Always return the selector switch to the OFF position after finishing with the ohmmeter. If you fail to do this, the battery may be dead the next time you try to use the meter.
- Do not touch both leads with your fingers.

Reading a meter

The principles for reading a meter are not that different from those used to read a common ruler. Figure 3 shows the scale of a 10 amp ammeter.

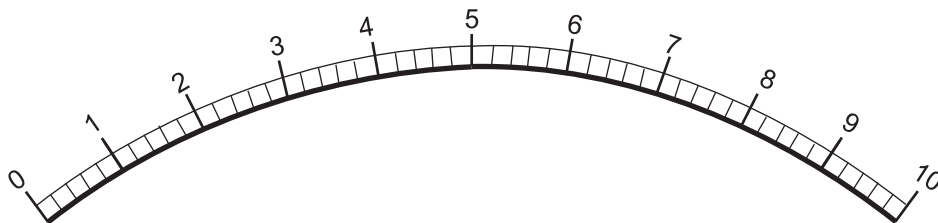


Figure 3—A 10 ampere ammeter scale

Notice that the scale has 10 larger divisions, each located next to a number. This type of scale, with equal spaces between each division, is referred to as a *linear scale*.

- From one of the larger divisions to the next is a difference of 1 ampere.
- Between each of the larger divisions are 5 smaller divisions. Each one of these divisions is equal to 0.2 ampere. (This value is arrived at by dividing the value of the larger division by the number of smaller divisions between each larger divisions. In this case $1 \text{ A} \div 5 = 0.2 \text{ A}$.)

Figure 4 shows the scale for a 50 volt voltmeter. This scale has 10 larger divisions. From one of the larger divisions to the next division is 5 volts ($50 \text{ V} \div 10 = 5 \text{ V}$).

Between each of the larger divisions are 10 smaller divisions, each representing 0.5 volts ($5 \text{ V} \div 10 = 0.5 \text{ V}$).

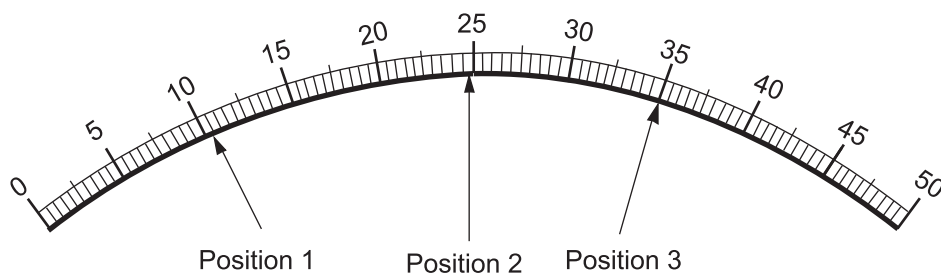


Figure 4—A 50 volt voltmeter scale

The arrows in Figure 4 represent the pointer position for three separate readings:

- Position 1 reads 10.5 volts. The pointer is past the 10 but before the 15, so the reading is 10 plus something. The pointer is 1 small division past the 10, so you must add the value of 1 small division (0.5) to the 10 ($10 + 0.5 = 10.5$).
- Pointer position 2 reads 24.5 volts. The pointer is past the 20 but before the 25, so the reading is 20 plus something. The pointer is 9 small divisions past the 20, so you must add the value of 9 divisions ($9 \times 0.5 = 4.5$) to the 20 ($20 + 4.5 = 24.5$).
- Pointer position 3 reads 35 volts. It is pointing directly at 35 so nothing more needs to be added.

Multi-range meters

Figure 5 shows a typical multi-range multimeter. At the top of the meter is the movement, which is calibrated with eight scales. Below is the range selector switch, used to select the scale and the type of quantity to be measured (e.g., DC milliamps, ohms, AC volts). This type of multimeter is referred to as a *VOM*, which stands for volts, ohms, milliamps.

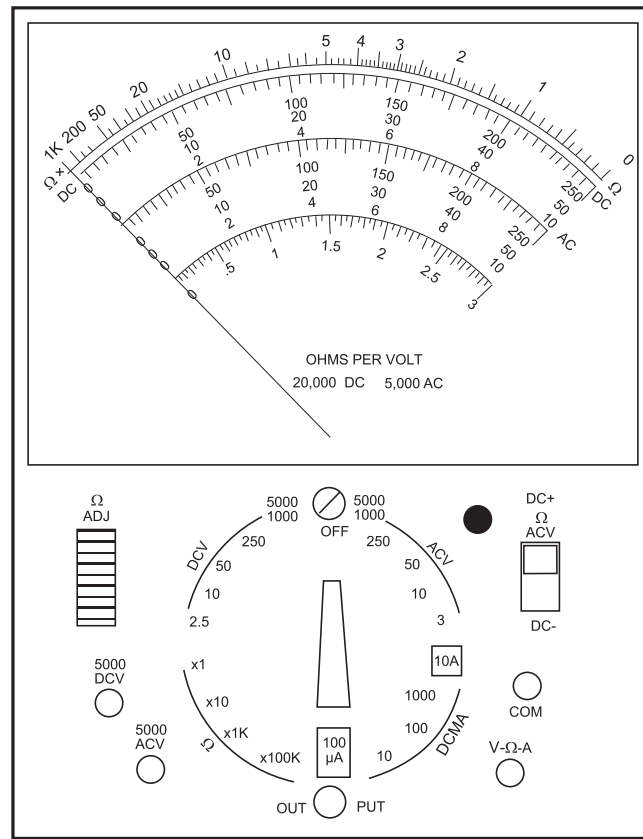


Figure 5—Multi-range multimeter

The position of the selector switch determines which scale to use when reading the meter. Figure 6 on the next page shows the same meter, but the range selector switch has been replaced with four arrows. This illustration of the meter has three pointers instead of one. This is unrealistic, but helps to explain how to use the meter.

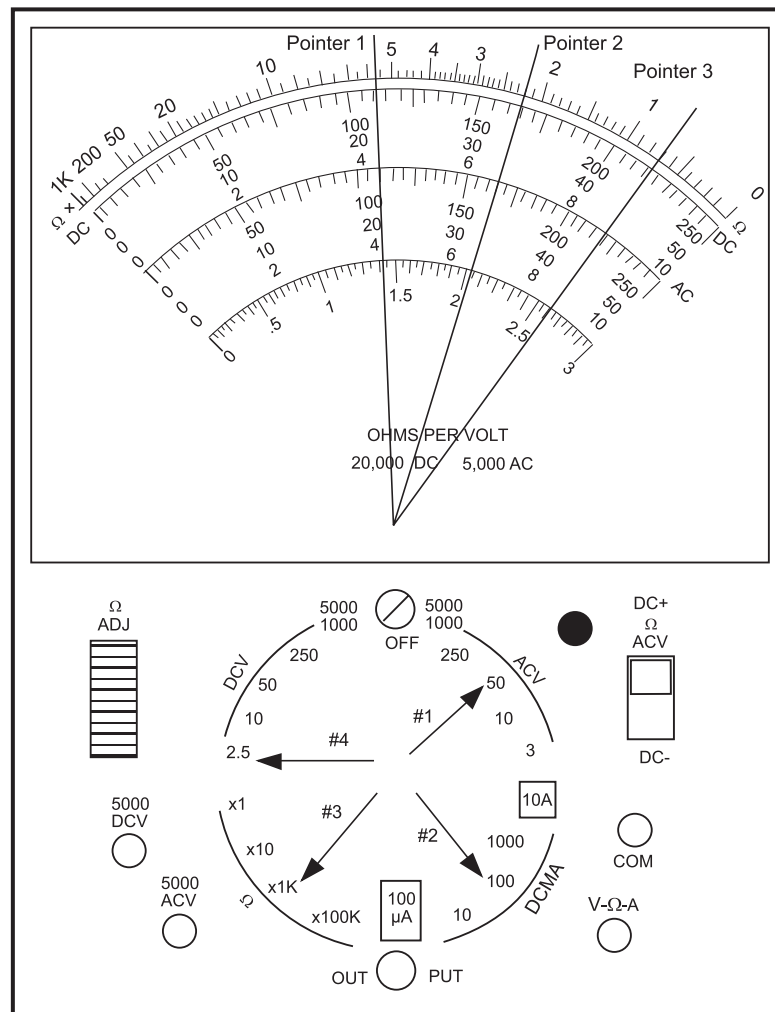


Figure 6—Multimeter

Here are some examples of how to read the meter.

Example 1

If the pointer is in position 3 and the range selector switch is in position 1, what does the meter read?

Step 1: The range selector switch is set to 50 volts AC. This means the meter will read 50 volts at full-scale deflection (all the way to the right). Look at the scales and find the one that is below the AC mark and ends with 50. Use this one.

Step 2: The pointer sits above the 40 but below the 50. Each small division equals 1 volt. The pointer is 3 small divisions above the 40, so the meter reading is 44 volts.

Example 2

If the pointer is in position 2 and the range selector switch is in position 2, what does the meter read?

Step 1: The range selector switch is set to 100 mA DC. This means the meter will read 100 mA at full-scale deflection. Look at the scales and try to find one that is below the DC mark and ends in 100. There isn't one. Look for one that ends in a number that when multiplied or divided by 10 gives 100. The 10 would work ($10 \times 10 = 100$). This means that you use the 10 scale but multiply the numbers on the scale by 10 when you read them.

Step 2: The pointer sits above the 60 (6×10) and below the 80 (8×10). Each small division equals 2 mA ($.2 \times 10$). The pointer is 3 small divisions above the 60, so the meter reading is 66 mA.

Example 3

If the pointer is in position 1 and the range selector is in position 3, what does the meter read?

Step 1: The range selector switch is set to the $\times 1000$ ohms range. Note again, the ohms scale reads in the opposite direction to the other scales. Zero is on the right and infinity is on the left. There is only one ohms scale.

Step 2: Because you are on the $\times 1000$ range, you must multiply everything you read on the ohms scale by 1000. The pointer sits above the 5000 mark but below the 10 000 mark. Each small division equals 500 Ω , so the meter reading is 5500 Ω .

Table 1 gives readings for all possible combinations of switch and pointer positions. The readings are given to the closest division. Check to see if you get the same readings.

Table 1: Meter readings

Switch position	Pointer 1	Pointer 2	Pointer 3
1	22 V AC	33 V AC	44 V AC
2	44 mA DC	66 mA DC	86 mA DC
3	5500 Ω	2200 Ω	700 Ω
4	1.10 V DC	1.65 V DC	2.15 V DC



Now do Self-Test 10 and check your answers.

Self-Test 10

1. What will happen if you connect a DC meter with wrong polarity?

2. The type of reading error that takes place when you do not look at the needle straight on is referred to as _____ error.

3. Voltmeters must be connected in _____ with the device across which the voltage is being measured.

4. What are the three ratings you must be careful not to exceed when you are using a wattmeter?

5. Ammeters must be connected in _____ with the device through which the current is being measured.

6. If a VOM meter does not have an OFF position, where should the range selector switch be left when the meter is not being used?

7. Why should the VOM meter never be left on an ohms setting when the meter is not being used?

8. What must you remember to do every time you switch ranges on an ohmmeter?

9. Using the meter shown in Figure 1, complete the readings in the table below.

Table 1: Meter readings

Switch position	Pointer 1	Pointer 2	Pointer 3
1			
2			
3			
4			

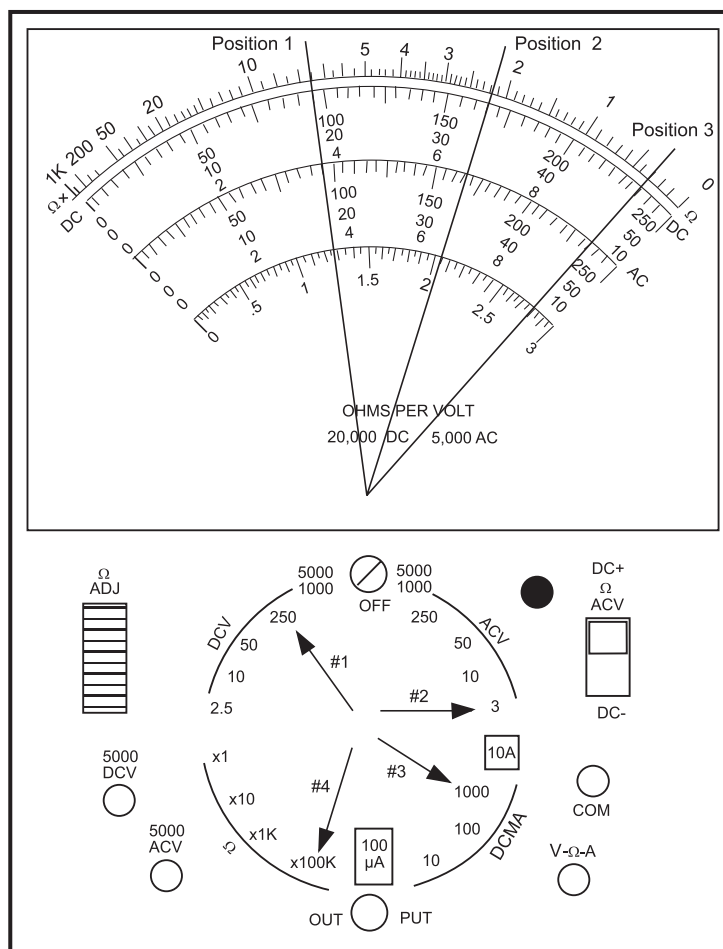


Figure 1—Multimeter for Question 9

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

Learning Task 11:

Describe features of resistors

Resistors

A resistor is an electrical component that introduces a specified amount of resistance into a circuit. Controlled resistances are often deliberately placed in circuits so as to limit current, provide a change in voltage or produce heat. A common method of controlling voltages and currents is through the use of resistors.

Resistor ratings

Resistors are rated according to their resistance value and their wattage. As the watts rating of a resistor increases, so does its physical dimensions. Many of the colour-coded resistors have a tolerance rating also. This tells you what the nominal resistance value may vary by. Wire wound resistors often have their ratings printed on them. Colour-coded resistors are identified by colour bands.

Resistor types

Resistors are made from many different materials and they are available in many different packages. Some resistors come in DIP (dual in-line) packages. Some are fixed resistance and some variable. Some, like photo-resistors are light sensitive; their resistance dropping sharply when exposed to light.

Resistors may be fixed, variable or adjustable.

Fixed resistor

There are three main classes of fixed resistors: the wire-wound resistor, the film resistor, and the carbon-composition resistor.

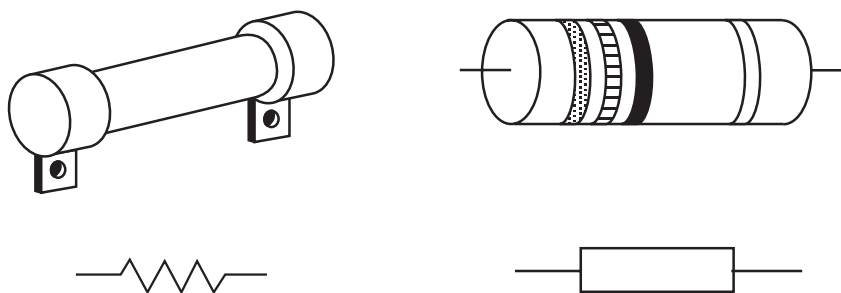


Figure 1—Fixed resistors and symbol

Wire-wound resistor

Wire-wound resistors are commonly used for the higher wattage ratings. Nichrome wire is frequently used. This is covered with a ceramic or hard plastic that acts as an insulating material. They are made in sizes from a fraction of an ohm to thousands of ohms.

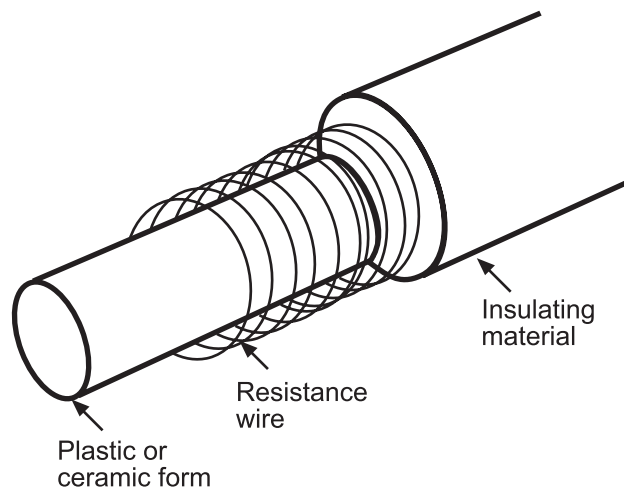


Figure 2—Wire-wound resistor

Film resistor

Film resistors are made by coating a non-conducting tube with a resistant material such as a carbon compound, nickel-chrome, or metallic oxide. The resistor is encased with a hard insulating material. Film resistors can be made almost as accurately as the wire-wound types and are often used in their place.

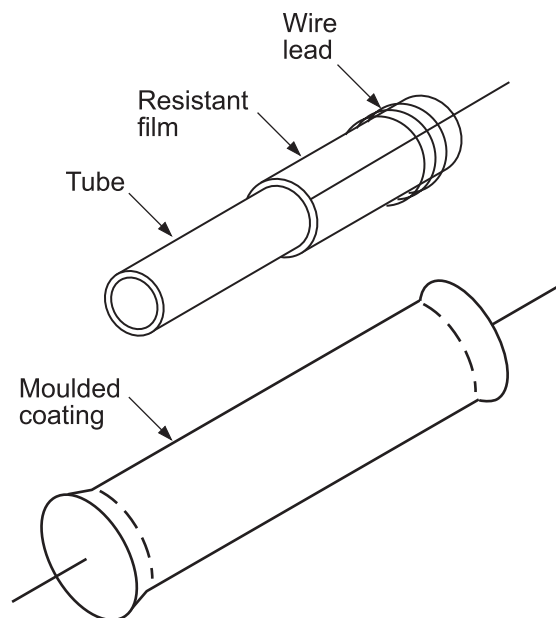


Figure 3—Film resistors

Carbon composition resistor

Carbon composition resistors are found in many low-current circuits. These resistors cannot handle much current and are limited to a maximum of 2 watts, depending on their size. They are small, rugged, and inexpensive. These resistors are made by combining carbon with an

insulating material. The resistor is usually a cylindrical-shaped component with connecting wires firmly attached. Color bands are baked on their hard outer shells. These color bands are used to indicate the ohmic value of the resistor. This resistance is constant and cannot be changed. They range in sizes from 10 ohms to many megohms.

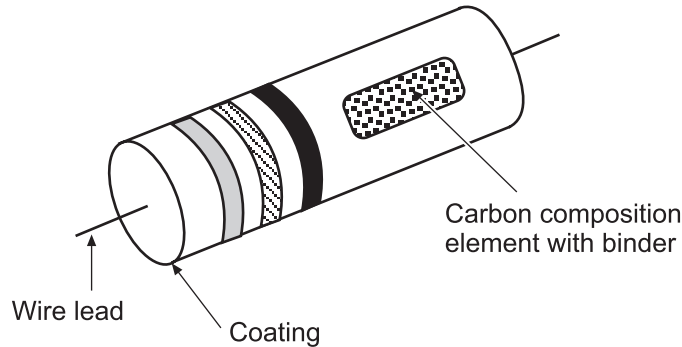


Figure 4—Carbon composition resistor

Variable resistor

An example of a variable resistor is on the volume control of an amplifier. By rotating a shaft, the resistance value is changed, as a movable contact slides along a resistive element.

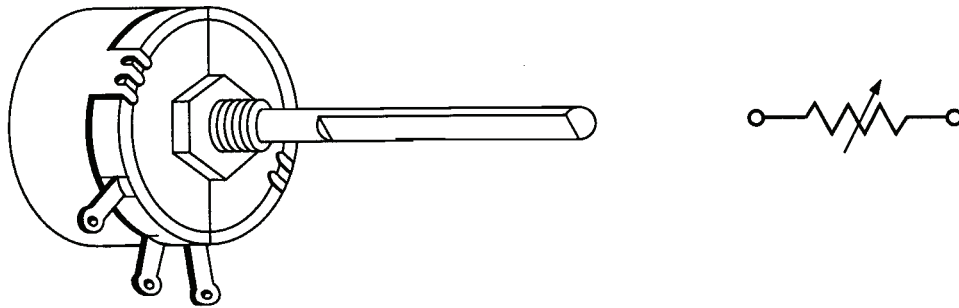


Figure 5—Variable resistor and symbol

Adjustable resistor

These resistors are not designed to be continually changed. Usually, they are initially set, and then left in that position to suit the application. Most are wire-wound, with the sliding collar being locked at some point on the coil to give the desired resistance. The separation between the middle terminal and the outer terminals determine the resistance value.

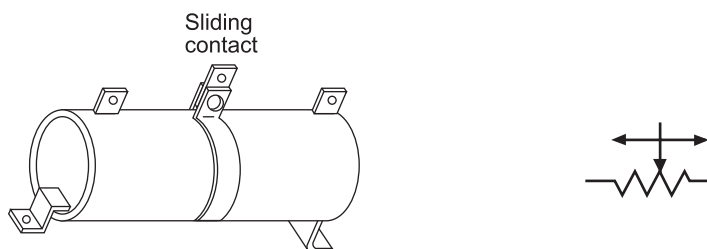


Figure 6—Adjustable resistor and symbol

Colour code

Carbon composition resistors have three or four bands. The fourth band indicates the tolerance of the resistor. The third band indicates the multiplier, and the first two bands indicate the numbers. Table 1 outlines what the colors stand for.

Table 1: Carbon composition resistor colour-code table

Colour of bands	Numerical value of first and second colour band	Multiplying value third band	Percentage tolerance fourth band
Black	0	1	–
Brown	1	10	–
Red	2	100	–
Orange	3	1000	–
Yellow	4	10 000	–
Green	5	100 000	–
Blue	6	1 000 000	–
Violet	7	10 000 000	–
Grey	8	100 000 000	–
White	9	1 000 000 000	–
Gold	–	0.1	5%
Silver	–	0.01	10%
No colour	–	–	20%

Example

What is the value of the resistor shown in Figure 4?

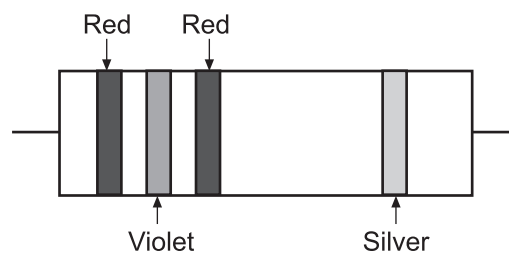


Figure 7—Resistor

First band is red = 2

Second band is violet = 7

Third band is red = 100. This is the multiplier.

Therefore, the nominal value of the resistor is $27 \Omega \times 100 = 2700 \Omega$

The fourth band is silver = 10%. This means the actual resistance could be 10% higher or lower than the nominal value.



Now do Self-Test 11 and check your answers.

Self-Test 11

1. For what three purposes are resistors used?

2. In what unit is a resistor rated?

3. Identify three types of fixed resistor.

4. Which resistor type has the lowest watts rating?

5. What is the nominal resistance of a colour-coded resistor having green on the first band, blue on the second and yellow on the third band?

6. If the fourth band on a colour-coded resistor is silver coloured, what is the tolerance in percent?

7. Adjustable resistors are usually of what type?

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

Learning Task 12:

Describe features of switches

Switches

Switches control the flow of current in a circuit by opening and closing the circuit. In most instances they either let current flow freely or block current completely. The switch is neither a power source nor a load; it is a controller. It neither absorbs energy like a load, nor converts energy like a generator. It is the link between the load and the source.

Most switches are manually operated. Some switches used in industry are operated by such things as air pressure, liquid level or pressure, temperature changes and so on.

The internal operating method of most switches consists of a fixed contact and a movable contact. When the toggle or lever is moved to ON, the movable contact touches the fixed contact and completes the circuit between the voltage source and the load. In nearly all switches a spring aids the movement of the contacts, causing them to open and close very quickly. This is necessary to minimize arcing.

Switches must open all live conductors to a load. Thus, lamps and devices in general that operate on 120 V AC require a *single-pole switch*. Switches that control 240 V loads are *double pole*, meaning they open and close both of the two hot lines; three-phase loads require *three-pole switches*.

Switches should have their rated voltage and current marked on them. The loads they control should not exceed these values.

There are hundreds of different switches used throughout the electrical industry. Many of these are housed in large enclosures and are used for large industrial loads. At this juncture we will examine only the operation of the switches used extensively to control lights in our homes, offices and industry.

Snap switches

Snap switches are used to control incandescent and fluorescent lamps. The three most common types of snap switches are the single-pole switch, the three-way switch and the four-way switch.

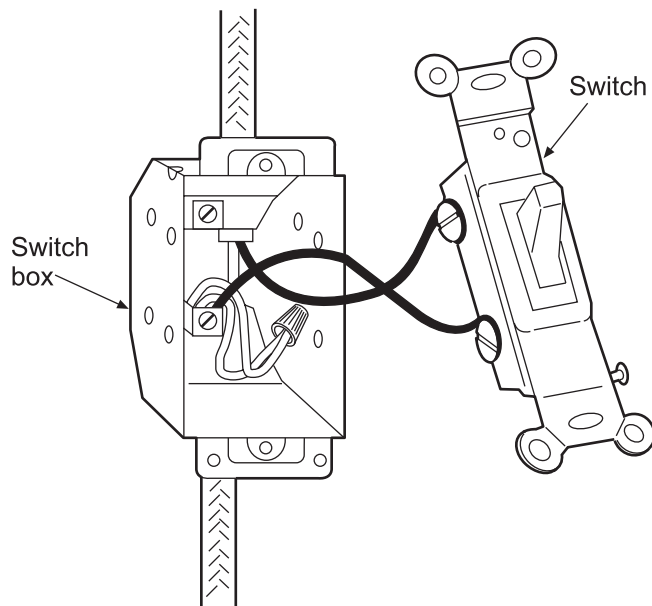


Figure 1—Snap switch used to control a lamp

Single-pole switch

The single-pole switch is the most common. In the ON position, the switch toggle (operating handle) is up; and in the OFF position, the toggle is down. Figure 2 shows a schematic and a wiring diagram of a single lamp controlled by a switch. Several lamps could be controlled using the same switch.

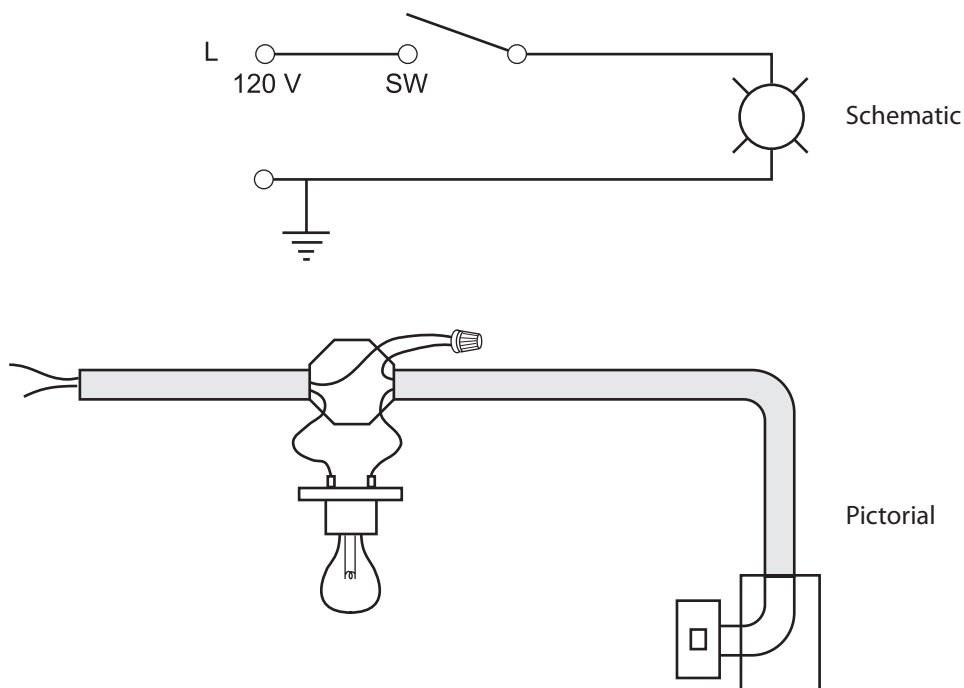


Figure 2—A lamp controlled by a single-pole switch

Three-way switch

Three-way switches are used to control a light from two different locations, for example, from the top and bottom of a stairway. The switch has three terminals, and it does not have an ON or OFF position. These switches are used in pairs, as shown in Figure 3.

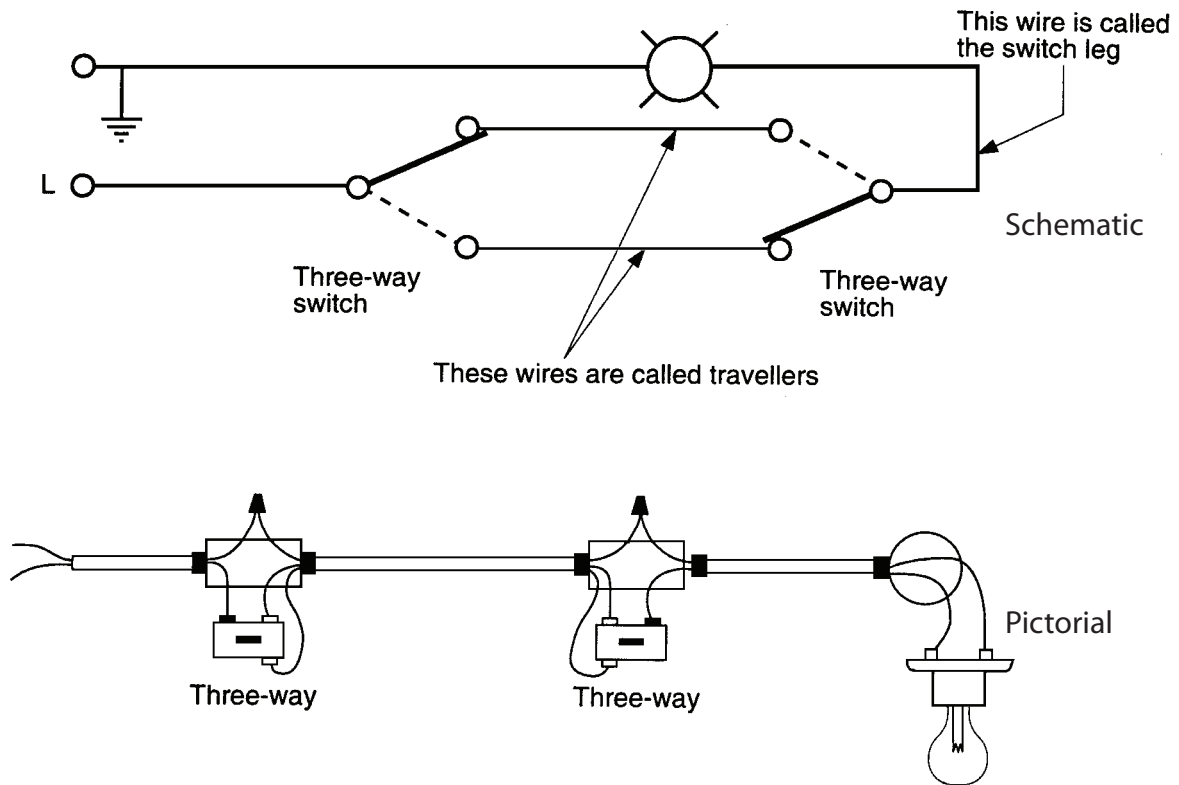


Figure 3—Three-way switches controlling a lamp

Four-way switch

These switches are used when one or more lamps are to be controlled from three or more locations. They are used in combination with three-way switches. An application would be in a long hallway or on two flights of stairs. Like the three-way switch, the four-way switch does not have an ON-OFF position. These switches have four terminals. Figure 4 shows four-way switches controlling a lamp.

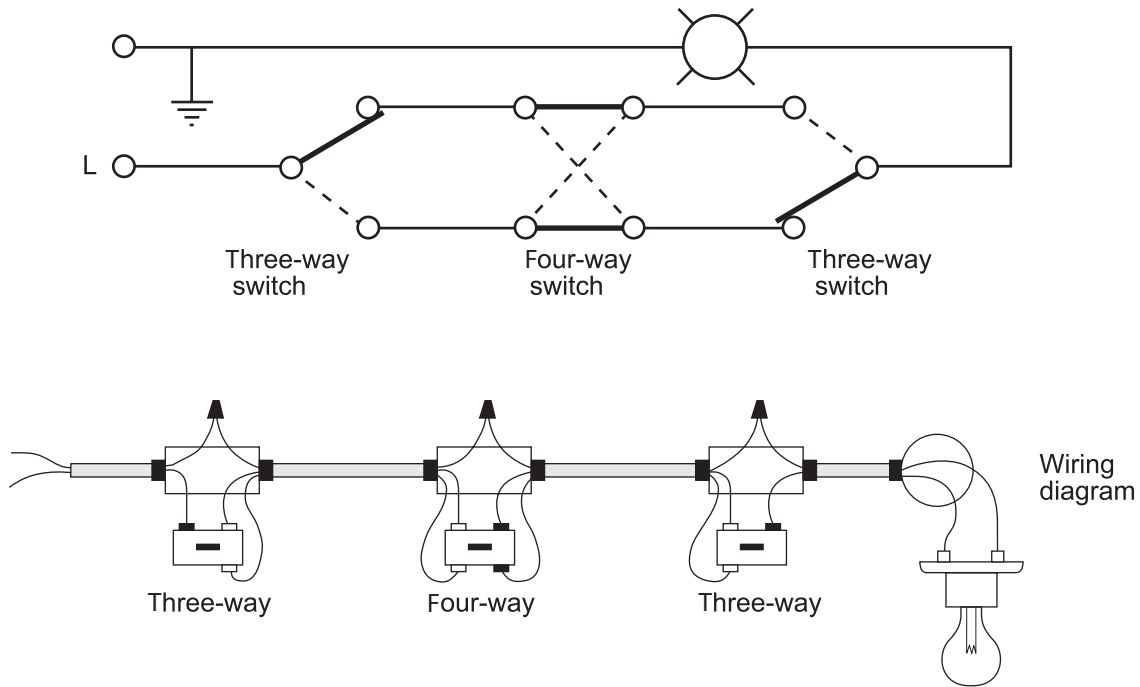


Figure 4—Four-way switches used to control a lamp

Dimmer switch

Dimmer switches are frequently used with incandescent lamps. This switch can regulate the light output from full brightness to zero light output. A dimmer switch is both cheap and efficient. It operates using electronic circuitry. The most common type of switch has a rotary control knob (Figure 5). Slider control types are also available.

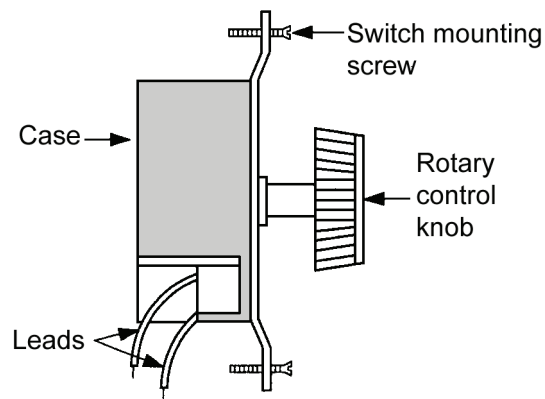


Figure 5—Incandescent dimmer switch



Now do Self-Test 12 and check your answers.

Self-Test 12

1. A switch is a device that automatically trips on excessive current.
 - a. True
 - b. False_____
2. By definition, a switch is a device that must be manually operated.
 - a. True
 - b. False_____
3. In nearly all switches, what is it that accelerates the opening and closing of the contacts?

4. If a load is supplied from two hot lines the switch need open only one line.
 - a. True
 - b. False_____
5. Four-way switches are required when a lamp is to be operated from more than _____ positions.
6. What ratings should switches have marked on them?

7. Why is it important that switch contacts part quickly?

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

Learning Task 13:

Describe features of circuit protective devices

Fuses

A fuse is an overcurrent device designed to open the circuit should the current exceed the rating of the fuse. Its function is to break the circuit before damage is done. Fuses are designed to be the weakest link in the electric circuit. So when the capacity of the circuit is exceeded, the fuse melts open first and protects the circuit. The fuse consists of an *element* or *link*, housed in a protective enclosure.



Figure 1—Fuse symbols

Operation

The fuse is a heat-sensitive device that contains an element of metal alloy. This alloy has a slightly higher resistance, than the conductors it protects but its melting point is much lower. The higher resistance causes the element in the fuse to heat up before the conductors in the circuit overheat.

A fuse does not *instantly* open when the current exceeds its rated value. The fuse element within the fuse responds to the heat generated by the flow of current through it. When the current level exceeds the fuse's rating, the link begins to melt open. The fuse does not always open instantly when its ampere rating is exceeded. The time it takes to melt and open the fuse element is inversely proportional to the magnitude of the current. Thus, a fuse will open almost instantly on a heavy fault current, but more slowly on an overload current.

Fuse types

Although the fuse is essentially a very simple device, many types of fuses are available for different applications. Besides having different voltage and current ratings, they come in hundreds of different shapes and sizes. They have different response characteristics, different current-limiting capabilities, and different shapes and lengths, and there are many specialty applications. As a general rule, the higher the amperage and voltage rating, the larger and longer the fuse will be. Some fuses are *time delay* types: under some conditions they take more time to melt and open. Some fuses have renewable links.

Fuses are used in homes, offices, industry, automobiles, ships, electronic equipment and almost anywhere electrical equipment is used. This Learning Task discusses only the more common ones found in buildings.

Cartridge fuses

These fuses are so named because their cylindrical shape resembles a shotgun cartridge. The ends of the fuse may be ferrule-contact or knife-blade contact.



Figure 2—Ferrule type and knife-blade type cartridge fuses

The construction of these two fuses is similar, but the knife blade end is used on fuses rated above 60 A. Fuses rated for 600 V will be longer than fuses rated for 250 V.

Plug fuses

These fuses are sometimes called the *screw-in fuse* or *Edison-base fuse*. These were quite common in wiring installations in homes at one time, but they have largely been replaced by circuit breakers. However, they are still commonly used in domestic ranges and are still seen in many older installations. At one time they had a serious shortcoming: a fuse of much higher ampere rating could replace a smaller fuse. Today regulations call for plug fuses to be designed to prevent this. Some of these fuses are shown in Figure 3.

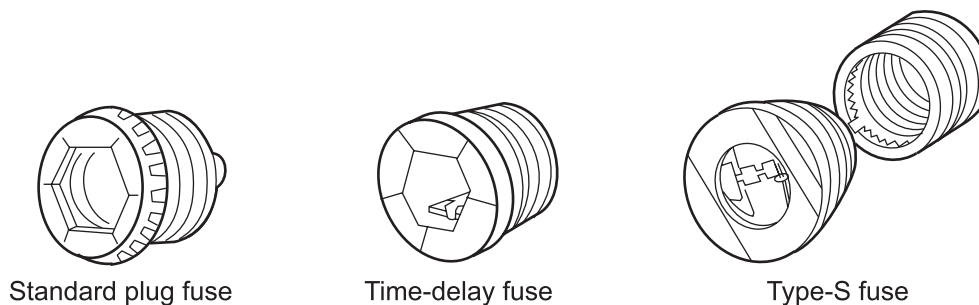


Figure 3—Plug fuses

Renewable link fuses

The renewable link fuse can be used repeatedly because the element can be replaced. This is in contrast to a one-time fuse, in which the element and body are discarded if the fuse blows. A disadvantage of this type of fuse is that it is possible to install a larger link, compromising the integrity of the installation.

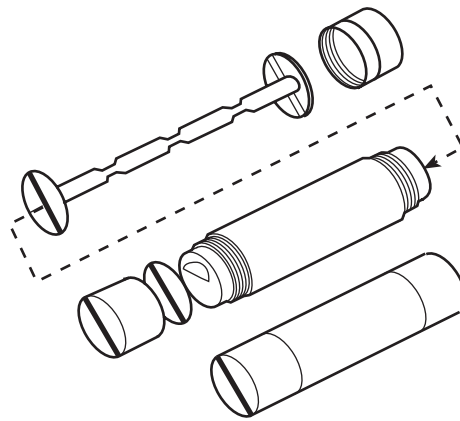


Figure 4—Renewable-link fuse

Circuit breakers

Shortly after the fuse was introduced, a rapidly expanding electrical industry began searching for an alternative method of providing protection for the electric circuit. Although most reliable when used properly, the fuse had the disadvantage that it had to be removed and replaced every time it opened. A device was needed that would not need replacing each time it operated, and could be easily reset to restore the power. Out of this search came the development of the circuit breaker.

A *circuit breaker* is an electromagnetic device that will open the electric circuit without injury to itself, and can be used over and over again. Circuit breakers may be operated magnetically to respond quickly, or they may be operated by thermal action that requires a time interval that depends on the magnitude of the current.

Circuit breakers may be single-pole, double-pole or three-pole. In the latter two, an excessive current in any phase will open the other line(s) also. Circuit breakers are made by several different manufacturers and are installed in pre-assembled cabinets. Unlike many other wiring components, circuit breakers are not interchangeable among different manufacturers.

Standard circuit breakers are rated in amperes, and like all other equipment, they must be rated for the voltage of the system that they are used in. Standard current ratings up to 100 A are 15, 20, 30, 40, 50, 60, 70 and 100 A. They are made in larger sizes also. The circuit breakers used mostly for domestic purposes would be 15 A size for lights and plugs, 20 A for heaters, 30 A for clothes dryers and 40 A for ranges. The most common type of circuit breaker is the moulded-case circuit breaker, but other types with lower current ratings are available for use in the auto industry and other specialized industries.

Circuit breakers in the system

Figure 5 shows how circuit breakers are used throughout the supply system. The circuit breaker closest to the fault should trip first. The circuit breakers protecting the branch circuits have the lowest current rating. These should trip if a fault develops in the branch circuit. These are backed up by other circuit breakers rated at progressively higher ampere ratings as you move upstream. This way selective protection is achieved.

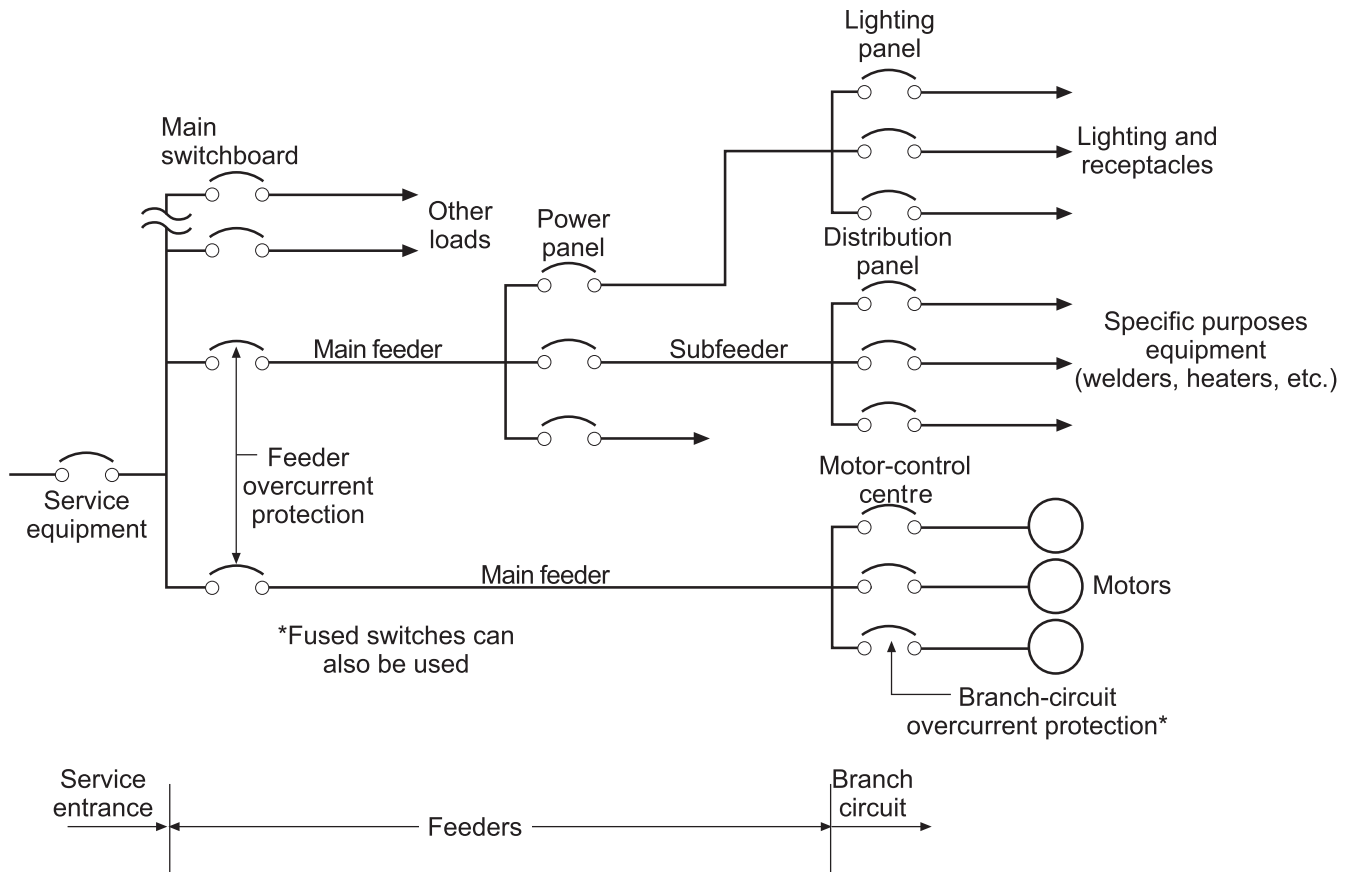


Figure 5—Circuit breakers in the system

For the moulded-case circuit breaker, all components are mounted inside a frame of insulating material. Each type of moulded case is identified on the frame by the manufacturer's letters. This identification refers to certain characteristics of the circuit breaker, such as its maximum allowable voltage and current, interrupting capacity and physical dimensions. Each manufacturer has its own identification system, as the circuit breakers have unique characteristics. Figure 6 illustrates a three-pole and single-pole type.

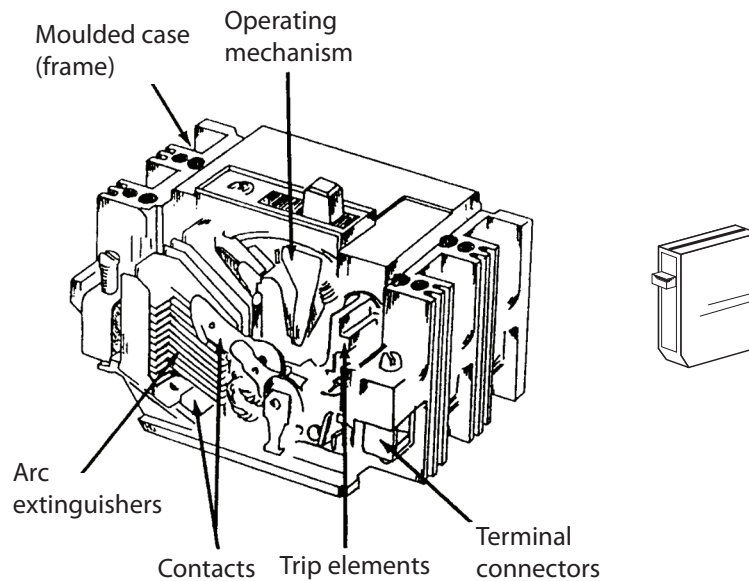


Figure 6—Three-pole and single-pole moulded-case circuit breakers

Operation

A handle turns the circuit breaker ON and OFF. It is a quick-make, quick-break type, meaning that the speed at which the contacts snap open or closed is independent of how fast the handle is moved.

The circuit breaker is also *trip-free*, meaning it cannot be prevented from tripping by holding the handle in the ON position. When the breaker trips, the handle moves midway between the ON and OFF position. To reset, the handle must be moved from the centre position to OFF, then to ON.

Trip elements

Trip elements trigger the operating mechanism in the event of a prolonged overload or excessive current magnitudes, and cause the circuit breaker to open. This triggering is done by either a thermal trip or a magnetic trip element. Many circuit breakers have both types of trip elements.

Thermal trip element

This heat-sensitive element is a bimetal strip composed of two dissimilar metals. The metals have a different rate of expansion, so heat from excessive current or overload will cause one of the metals to bend. This bending releases a latch that opens the circuit.

Magnetic trip element

Current passing through the circuit breaker goes by way of a small electromagnet. Should a short circuit or heavy fault current flow in the breaker, the electromagnet attracts an armature attached to the trip bar. This causes the contacts to open quickly.



Now do Self-Test 13 and check your answers.

Self-Test 13

1. Draw two common symbols for a fuse.
2. When a link in a fuse melts, it gets an assist from a spring to open quickly.
 - a. True
 - b. False
3. The time it takes a fuse to open a circuit is inversely proportional to what item?
4. What is the more common name for an Edison fuse?
5. What shortcoming did the original Edison fuses have?
6. Name an advantage and disadvantage of a renewable link fuse.
7. The knife-blade end is used in cartridge fuses having a current rating in excess of what amperage rating?
8. What advantage does a circuit breaker have over a fuse?
9. Circuit breaker may operate by _____ action or by _____ action.

10. What is the most common type of circuit breaker used today?

11. What is meant by the term *trip-free* with reference to a circuit breaker?

12. Circuit breakers are available in what sizes up to 100 A?

13. Circuit breakers of the same ampere rating are interchangeable from one manufacturer to the next.

a. True

b. False

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

Learning Task 14:

Describe the characteristics of common conducting materials

Conducting materials

A material that allows electrical current (electrons) to flow with relative ease is known as a *conductor*. The ideal electrical conductor is a material that will carry the greatest amount of current with the lowest temperature rise. In practice there are other important criteria for the selection of a conductor material. A brief discussion of these criteria follows.

Cost

Silver has a low resistivity value but is very expensive.

Weight

Aluminum is not as good a conductor as copper, but it is used extensively as a conductor because it has only 30% of the weight of copper.

Oxidation

Aluminum oxidizes more quickly than copper, but the potential for resistive buildup is offset by the low cost of aluminum.

Ductility

Ductility is the ability of a material to be drawn into a wire. The finer the wire needed, the more ductile the material must be.

Malleability

This the ability of a material to be rolled or hammered into thin sheets. Thin foils are used in some resistors and in electronic applications.

Ultimate strength

The amount of mechanical stress a wire will withstand before breaking is called its *ultimate strength*. Aluminum wire does not have enough ultimate strength to support its own weight when strung great distances, as in power lines.

Oxide resistance

The surface of a conductor can oxidize. The oxide that forms does not affect the resistance of the conductor but can have a marked effect on connections and terminations.

Contact resistance

This is the resistance per area of contact between two conductors at a given pressure. Contact resistance varies with the type of material used as a conductor.

Conductance

Conductance may be thought of as the opposite of resistance. A good conductor has high conductance and low resistance.

Another consideration is the amount and quality of the insulation a conductor may need. Insulation is discussed in Learning Task 15.

The relative properties of several conductors are shown in Table 1. Copper is used as the standard against which the other materials are compared. The ultimate strength, weight, area size, contact resistance and cost of copper have been arbitrarily set at 100 so that comparisons are easy to make.

Table 1: Conductor comparisons

	Copper	Aluminum	Silver	Gold	Steel
Conductance	very good	fair	excellent	good	poor
Resistance	10.4	17.0	9.6	14.4	75.0
Oxidation	slow	fast	slow	very slow	very fast
Oxide resistance	high	very high	very low	perfect	very high
Ductility & malleability	very good	poor	good	excellent	poor
Ultimate strength	100	72	–	–	185
Weight	100	30	120	217	88
Insulation required per volume	100	163	92	139	721
Contact resistance	100	700	90	90	–
Cost by weight	100	50	9600	640 000	4

Several observations can be made from Table 1:

Gold and silver are expensive and so are rarely used for conducting wires. However, due to their slow oxidation rate, excellent to good conductivity and high malleability, both are used in thin layers on electronic contacts.

Copper is an excellent conductor and is often used for conductors. It is easy to work with and does not oxidize as much as aluminum or steel. Copper is also used in electronic circuits because it solders readily and ensures secure electrical connections. Copper wire splices must be made secure to prevent the oxide coating from reducing the current-carrying ability of the splice. Copper has become expensive, however, and a substitute is being sought.

Aluminum is lighter than copper but is not as good a conductor. To obtain the same current-carrying capacity, an aluminum conductor must be slightly larger than one made of copper. Using aluminum poses three other major problems: *rapid oxidation*, *electrolysis* and *cold flow*:

- Aluminum oxide forms easily, acts as an insulator and reduces the flow of current. Antioxidant chemicals are available to prevent oxidation of the wire. These chemicals are usually applied with a brush, forcing the chemical into the strands of the cable.
- Electrolysis is the chemical breakdown of two metals reacting with one another. Aluminum reacts with some metals in this way. The process is accelerated by moisture and the flow of current in the conductors. Approved connection devices resist electrolysis. You must use approved terminal splice connectors.
- Cold flow causes the connection points to lose their grip. A terminal screw can be tightened firmly, but in a few days, the aluminum will accept the new shape into which it has been forced. This reduces the pressure of the terminal screw on the wire, and the aluminum flows into the new shape. This cold flow results in a loosened connection. As a result, the terminal connection will overheat, causing damage to the connection and insulation.

If handled properly, aluminum is an effective conductor that will provide many years of service.

Steel is the strongest and cheapest of the three metals and is used mainly as a supporting material. For example, aluminum and copper cables are often wound around a steel core for outdoor wiring. Conductors made this way can withstand a great deal of stress. Also, electric railway or subway supply systems often use steel rails as conductors. The rails are sometimes made of special steels containing a small amount of copper to improve their current-carrying ability.

Steel conduit and boxes are not used to carry current for the operation of electrical equipment, but these enclosures are used to complete the grounding circuit. Manufactured grounding electrodes use either two steel rods driven into the ground or a buried steel plate, to provide a ground connection for the grounding conductor from a building's electrical service equipment.

Conductor forms

Now that we have discussed what conductors are made from, we will look at what most conductors are made into. The most common form of electrical conductor is the wire. Most electrical wires are made from copper or aluminum and are in one of two forms—solid or stranded.

Solid conductors

Solid copper wire is usually made by drawing a soft copper rod (from 6 mm to 13 mm in diameter) through a series of doughnut-shaped metal blocks called *dies*. The hard centre of each successive die has a hole slightly smaller than the hole of the die through which the rod has just been drawn. As the rod passes through the dies, it is reduced in diameter and lengthened.

The wire tends to work-harden after passing through several dies. This hard-drawn copper is used for some outdoor wires because it is quite strong.

If the diameter needs to be still smaller, the wire is first passed through an annealing oven, which heats and softens it. The wire can then be further reduced to any size required. The annealing process may have to be repeated several times.

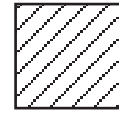
Solid wire is normally found in smaller sizes only. Usually it is used for sizes smaller than No. 8 B&S.

Bus bars

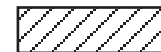
Bus bars are usually reserved for high-current applications in electrical distribution systems. Bus bars have many different shapes and are made mainly of copper or aluminum.

Figure 1 shows three typical cross-sectional shapes. Bus bars are used because they strengthen electrical distribution equipment and simplify its manufacture.

Solid square



Solid rectangle



Hollow tube

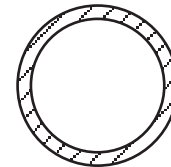


Figure 1—Typical bus bar shapes

Stranded conductors

Stranded wire is a collection of solid wires twisted or braided together, commonly around a central core. The current-carrying capacity of a stranded wire is close to the product of the number of strands and the current-carrying ability of a single strand. Stranded wires act as a single conductor and carry a single electrical current.

Stranded conductors are normally used on cable sizes No. 8 and larger. Ordinarily a stranded conductor has wires all the same size. The size of the strands used depends on the flexibility required. For example, No. 00 cable may be made up of seven strands of No. 7 wire, or 19 strands of No. 12, or 37 strands of No. 24, the last one being rated “extra flexible.”

Concentric stranded

Concentric stranded is the most commonly used type of conductor. Usually it consists of one control wire, surrounded by six strands.

If the cable requires more strands, another layer is added that consists of 12 strands, as shown in Figure 2. Each layer added has six strands more than the previous layer.

The total number of strands for the common types of concentric cables are therefore 7, 19, 37, 61, 91, etc.

Compact concentric round

Compact concentric round conductor is used where:

- A minimum diameter is required.
- A smoother surface for the insulation is required.
- The space between strands must be decreased so that impregnating compounds cannot flow (migrate) as freely.

Figure 3 shows how the wires are packed closely to eliminate spaces between them.

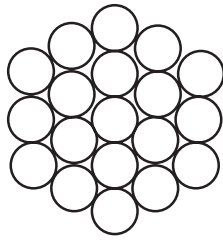


Figure 2—Concentric

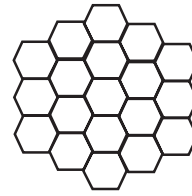


Figure 3—Compact concentric

Bunched stranded

Bunched stranded wire is a collection of wires twisted together in no particular geometrical arrangement. It is generally used for flexible cords and fixture wire in sizes No. 10 to No. 22.

For example, No. 18 lamp cord contains 16 No. 30 wires, loosely twisted together in the same direction.

Rope stranded

A rope stranded cable is a concentric-stranded assembly. It has several concentric cables twisted together concentrically. This type of construction is used in rubber-sheathed cords and cables in sizes 5 000 000 circular mils to No. 8 AWG.

Figures 4 and 5 show the cross-sections of bunched and standard rope stranded cable.

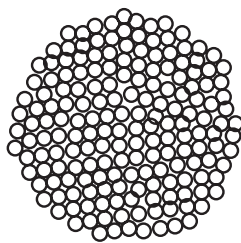


Figure 4—Bunch stranded

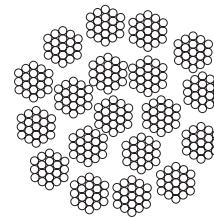


Figure 5—Standard rope stranded

Cables are made in forms other than circular cross section. There are many shapes and sizes of flat braid cable. One common use for flat braid cable is the battery-grounding strap on an automobile.



Now do Self-Test 14 and check your answers.

Self-Test 14

1. Ductility is the ability of a material to:
 - a. be flattened into thin sheets
 - b. be formed into a shape it will hold
 - c. be drawn into a wire
 - d. resist oxidizing

2. The amount of stress a wire will withstand before breaking is a measure of its:
 - a. malleability
 - b. weight
 - c. resistance
 - d. ultimate strength

3. State two reasons for the common use of copper as a material for industrial wiring circuits.

4. If a conductor is rated as having very good conductance, slow oxidation and very good ductility, the material is probably:
 - a. aluminum
 - b. silver
 - c. steel
 - d. copper

5. A conductor rated as having excellent conductance, very slow oxidation, good malleability and a cost factor of 9600 is probably made from:
 - a. aluminum
 - b. silver
 - c. gold
 - d. copper

6. State one advantage of aluminum over copper when aluminum is used as a conductor.

7. One advantage of stranded wire over a solid wire is its:
- a. ampacity
 - b. weight
 - c. cost
 - d. flexibility
8. In the manufacture of copper wire, the wire is pulled through a die. What two things happen to the copper during this process?
- _____
- _____
- _____
- _____
9. A material with a better conductivity rating than copper is:
- a. aluminum
 - b. gold
 - c. steel
 - d. silver
10. State the main reason for including steel as an electrical conductor in a cable.
- _____
11. State two major disadvantages of using aluminum as a conductor.
- _____
- _____
12. Flexible cords generally have:
- a. compact stranding
 - b. bunch stranding
 - c. segmental stranding
 - d. rope stranding

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

Learning Task 15:

Identify common insulating materials used for conductors

The purpose of conductor insulation is to prevent unwanted flow of electrical current, such as ground faults, short circuits or electric shock. To perform this function, conductor insulation must satisfy certain conditions:

- It must have a *voltage rating* suitable for the circuit application. If the insulation is stressed by too great a voltage, it may break down and conduct. The ability of a material to resist breakdown is called its *dielectric strength*.
- It must have a *temperature rating* to satisfy the circuit application. If too much heat is present, the insulation may melt or burn, leaving bare conductors. Placing insulation in areas with too-high temperatures greatly reduces the life expectancy of the insulation. A rule of thumb is that for every 10°C beyond normal rating, the insulation life is reduced by one-half.
- It must be appropriate for its *location*. For example, moisture can reduce dielectric properties, and toxic elements can cause deterioration of the insulation. The conditions of use must be suitable for the chosen insulation.
- It must be protected against *mechanical damage*. This may involve special installation techniques or additional coverings.

Insulating materials

To satisfy various conditions encountered in electrical installations, there are various ways to insulate conductors.

Enamel

Magnet wire is used in meter coils, small transformers, relays, motor windings and other electromagnetic applications. The strength of an electromagnet depends, in part, on the number of turns in its coil. The thickness of the insulation on a conductor is a factor in determining how many turns can be placed on the coil. Magnet wire is insulated by dipping it in varnish or enamel. Six or seven coats of enamel produce insulation that is very thin but that has a high dielectric strength. The insulation used on the magnet wire is:

- moisture- and chemical-resistant
- non-corrosive to copper
- high in heat transferability
- not too costly.

Varnished cambric

Insulating tape can be made from impregnated cloth. The cloth itself has low dielectric strength and is very hygroscopic (that is, it absorbs moisture). When properly impregnated with varnish,

the dielectric strength of cambric is greatly increased to about 1000 volts per mil, and it becomes only slightly hygroscopic. If you stretch this type of insulation too tightly, the varnish film may be broken or weakened, which would spoil its insulating capacity.

Rubber

Rubber is a common insulation. The term *rubber* normally includes natural rubber and silicone-base rubber. Rubber compounds are used where flexibility and abrasion resistance are of prime importance, as in extension cords and electrical welding cables. These materials are formulated in many ways for a variety of specific conditions. Some formulations are suitable for -55°C minimum temperatures while others are suitable for $+75^{\circ}\text{C}$ maximum temperatures.

Thermoplastics

Thermoplastic materials soften when heated, and conversely, harden as they cool. They also have the property of cold flow when subjected to high pressure, even at ordinary temperatures. These two characteristics must be kept uppermost in mind when using them. Cold flow may occur at a point of pressure concentration where a cable hangs over the edge of a cable tray. The warmer the plastic, the faster it will flow.

Polyvinylchloride (PVC) is a widely used thermoplastic. It may be identified by the flame test. When held in a flame it melts, drips and burns. When the flame is removed, PVC instantly self-extinguishes. PVC has a variety of trade names, such as Flameseal and Flamenol. PVC insulation is limited by the Code to an operation voltage of 600 V AC.

PVC is given identification letters by the Canadian Standards Association:

- *T type* is suitable for dry locations only.
- *TW type* is suitable for use in wet and dry locations.
- *TWU type* is suitable for direct burial in the ground.

The main limitation of PVC is temperature: it softens and flows at 150°C . When subjected to weight or pressure it flows at lower temperatures; therefore, the maximum conductor temperature allowed for PVC is 60°C . At low temperatures it stiffens and hardens, making it difficult to handle. Once installed, it is not affected by cold, but it must not be subjected to mechanical shock or vibration at low temperatures.

Cross-linked (or chemically vulcanized) *polyethylene* is surface-marked *XLPE* or *X LINK* as required by Table 19, Note 8 of the Code. It combines the excellent electrical properties of thermoplastic polyethylene with the thermal properties of a *thermosetting* material. As thermosetting materials are heated, they harden rather than soften or melt. This improves the electrical, thermal and mechanical properties of the insulation.

Minerals

Minerals are compounds of definite chemical composition, found in a natural state in the ground. They are not of vegetable or animal origin. For instance, coal is not a mineral. Minerals used for insulation are very stable and capable of operation at high temperatures. These minerals are mica and magnesium oxide.

Mica is an excellent insulator but is seldom used on cables. It is used mainly for very high temperature applications such as heating elements for toasters and irons.

Magnesium oxide is a powder with a very high resistance when dry. It is hygroscopic. When moist, its insulation resistance and dielectric strength drop considerably. The dielectric strength and thermal (heat) conductivity increase greatly when the powder is compressed. High thermal conductivity permits the heat from the conductor to flow away freely. This means that heavier current can be carried for a given size of conductor. Because of its properties, this material is used in a strong, moisture-proof sheath, usually copper. To keep moisture out, it must be properly terminated. One trade name is Pyrotenax. This type of cable is generally used where extremely adverse conditions may be encountered, such as heat, explosive atmosphere or chemicals.

Colour coding

Most electrical wiring circuits look complicated because several wires are found at any one point in the circuit. In order to make it easier to know exactly which is which, they are marked using one or two methods:

- Each conductor insulation is coloured.
- Each conductor insulation may have a labelled marker attached to it. On larger cables, this is a coloured strip.

The Canadian Electrical Code reserves two colours for specific applications:

- White or natural grey covering is reserved for insulated, identified conductors, identified common conductors and identified neutral conductors.
- Green covering is reserved for the *bonding conductor*.

When this system of colour coding is followed, at any point in any circuit a white wire always indicates a neutral conductor; except in the case when armoured cable, aluminum sheathed cable, or non-metallic sheathed cable containing an identified conductor is used for single-pole, three-way or four-way switch loops in accordance with Rule 4-034.2 of the Canadian Electrical Code. A green wire always indicates a bonding conductor. Any other colour wires, such as red, black or blue, can be assumed to be live or hot, meaning that they will have a voltage on the conductor and are therefore dangerous. See Figure 1.

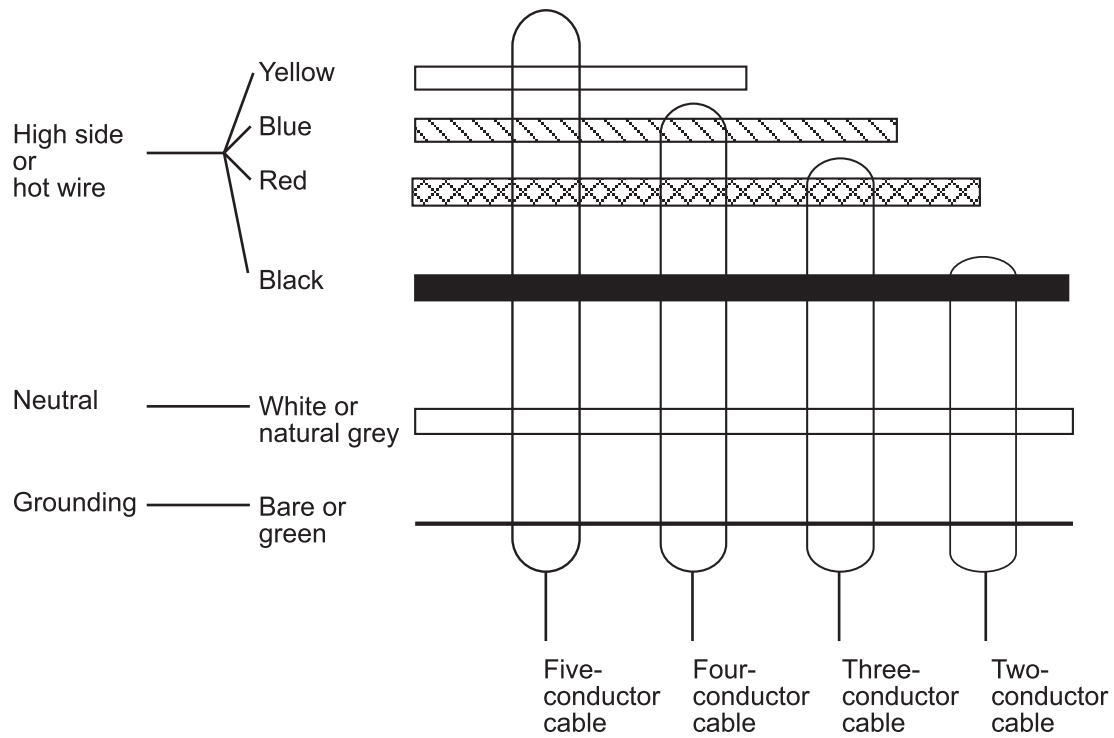


Figure 1—Insulation colour codes in general circuit use



Now do Self-Test 15 and check your answers.

Self-Test 15

1. Is mineral-insulated cable suitable for fire-resistant wiring? Explain.

2. What common characteristics do TW and TWH (TW75) have as insulating materials?

3. Varnished copper wire is used especially in the manufacture of _____ .

4. How do you recognize cross-linked insulation?

5. With respect to electrical circuit wiring, what colour of insulation is commonly used for:

- a. a ground wire _____
- b. neutral conductor _____
- c. a live or hot conductor _____

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

Learning Task 16:

Describe the applications of various types of conductors

Many different wires and cables are manufactured for numerous applications. For simplicity, we will identify and briefly describe four application categories commonly encountered: power circuit wiring; fixture wires; low-voltage control circuits; and communication, alarm and signal circuits.

Power circuit wiring

The term *power wiring* usually means conductor and cable installation for the distribution of electrical energy within residential, commercial and industrial buildings.

Service equipment

This normally uses the largest conductors in any installation and is the main power source for all other circuit wiring. These conductors usually require some degree of special mechanical protection. The Canadian Electrical Code (CEC) specifies types of conductors permitted for service equipment.

Branch circuits

These circuits supply such things as lighting, receptacle outlets, heaters, dryers, ranges and motors. They use a variety of conductor types, such as non-metallic sheath cable, armoured cable, mineral insulated cable, or thermoplastic- and rubber-insulated cable (usually in conduit).

Residential wiring uses non-metallic sheath cable almost exclusively—typically type NMD-90. Specific wiring methods will be discussed later. Figure 1 on the next page illustrates a few typical residential wiring circuits.

Fixture wires

A special type of wire is approved for use within electrical equipment such as lighting fixtures. It is usually a stranded, flexible wire with a high-temperature insulation designed for connecting internal fixtures to the power wiring conductors. This wire is usually specified as a higher temperature *equipment wire* in the CEC.

Communication, alarm and signal circuits

Communication and signal circuits are defined in specific sections of the CEC. Generally, these circuits are extra-low voltage and use shielded conductors. A typical example is an intercom system.

Intrusion (burglar) alarm and fire alarm circuits are commonly encountered by construction electricians. Fire alarm systems are also covered separately in the CEC. These circuits involve special wiring considerations that you will be learn about later.

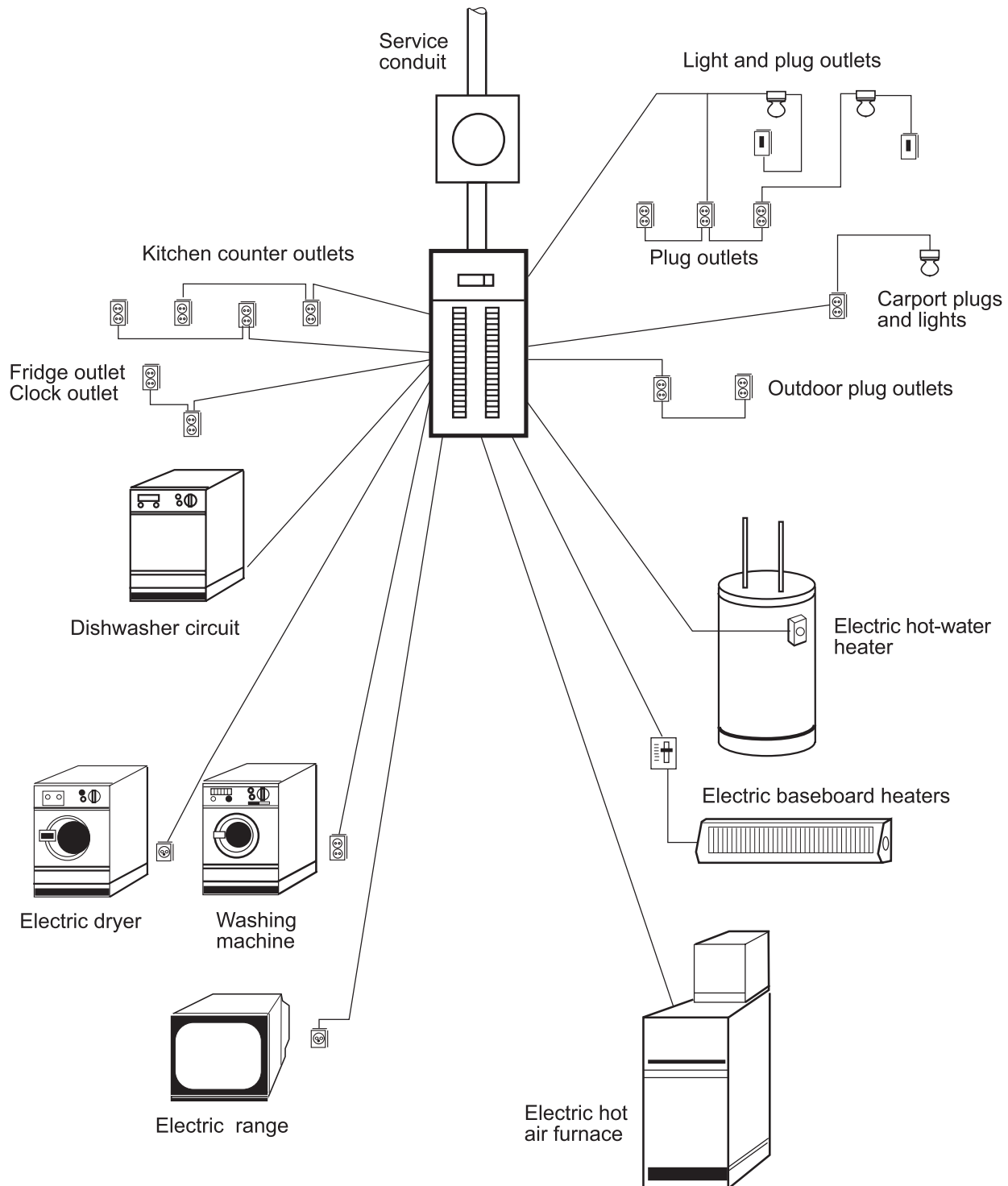


Figure 1—Typical power circuits for residential wiring

Low-voltage control circuits

The CEC defines *low voltage* as voltages from 31 V to 750 V inclusive. Some control circuits, such as those for motors, may operate at voltages as high as 600 V. The conductors for this application must be properly rated for this voltage value.

Other control circuits are classified as *extra-low voltage*, operating at 30 volts or less. Examples are doorbell or chime circuits, and residential thermostat circuits. These typically use *bell wire*, consisting of a two-conductor, twisted-pair cable made in AWG sizes No. 16 and smaller.

Figure 2 shows a 24 V remote-control wiring system commonly used in some lighting circuits.

These low energy control circuits and methods of wiring them are often described as Class 2 circuits in the CEC. Common examples of Class 2 circuits are circuits supplying relays, doorbells, buzzers and low-power electronic equipment.

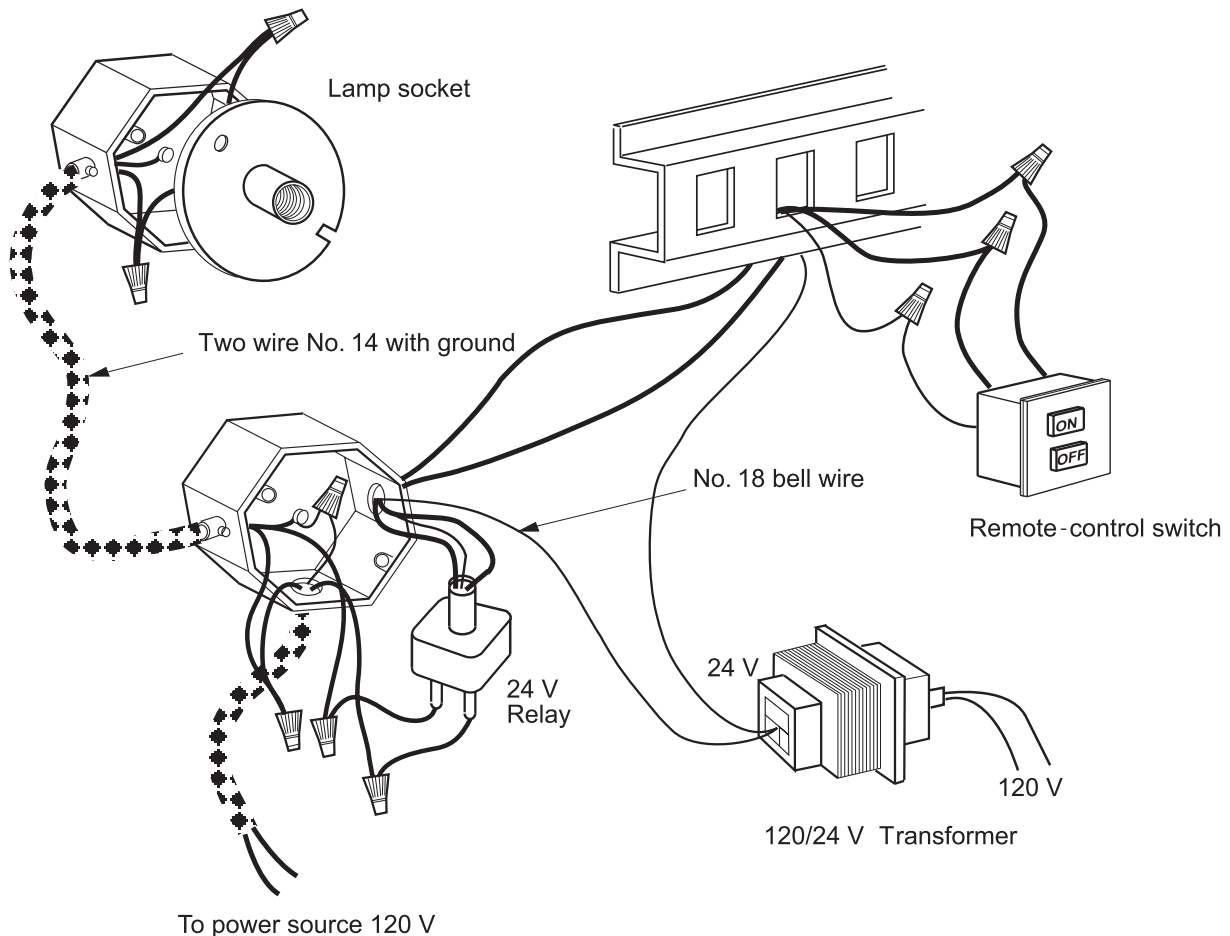


Figure 2—Low-voltage remote-control wiring system

Common wire cables

Numerous types of cable are used for wiring installations. A *cable assembly* consists of multiple single-conductors. They have either strands of wire making up one *individual conductor* or several individual circuit conductors contained within a *common assembly* or covering. The following types of cables are commonly used in wiring installations:

- Non-metallic sheathed cable
- Armoured cable
- Aluminum-sheathed cable
- Mineral-insulated cable
- Neutral supported cable
- Service entrance cable
- Flexible cord or cable

The CEC identifies the trade designation and constructional features of common cables, as well as their conditions of use.

Non-metallic sheathed cable

NMSC is the most commonly used cable for dwelling units. It usually has two or three insulated conductors, plus a bare ground wire, within an overall non-metallic (usually plastic) sheathing. It is sometimes called *loomex*. One NMSC type is shown in Figure 3.

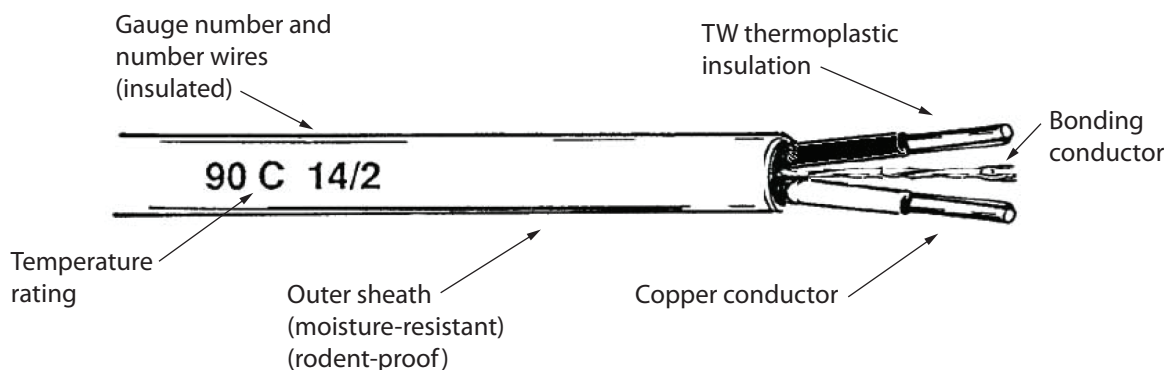


Figure 3—Non-metallic sheathed cable

The three categories of non-metallic sheathed cables are based on installation conditions:

- Type NMD90, where D stands for *dry or damp* locations and 90 stands for 90°C
- Type NMW, where W stands for *wet* locations
- Type NMWU, where U stands for *underground*

Since the outer covering of NMSC can be easily punctured, some applications may require extra mechanical protection. NMSC is limited to circuits not exceeding 300 V, and is used in buildings of combustible (wood frame) construction.

Non-metallic sheathed cable and many other cables contain PVC in their insulation or jackets. The Electrical Equipment Manufacturers Association of Canada (EEMAC) issues this warning through the manufacturers:

- Non-metallic coverings of electric cables can burn and may transmit fire when ignited.
- Burning non-metallic coverings may emit acid gases that are highly toxic and generate dense smoke.
- Emission of acid gases may corrode metal in the vicinity (such as sensitive instruments and reinforcing rods in cement).

Armoured cable

Armoured cables (AC) contain an interlocking, metal armor sheath to protect the insulated conductors inside. Because of the metallic sheath, it is commonly used in open wiring where there may be exposure to some mechanical abuse. For years it has been referred to as BX. Armoured cable is used in residential, commercial and industrial applications.

Similar to NMSC, it is available in different types based on its application:

- Type AC is limited to dry wiring locations only.
- Type ACWU contains a thermoplastic covering over the armour that makes it suitable for wet or even underground installations.
- TECK is a special type of armoured cable that is very popular for service installations and exposed wiring in other adverse conditions. TECK cable is available in single-conductor or multi-conductor form, typically in voltage ratings of 600 V, 1 kV or 5 kV. The insulated conductors are usually standard colour-coded. There are types suitable for use down to -40°C . Construction of TECK 90 cable is shown in Figure 4.

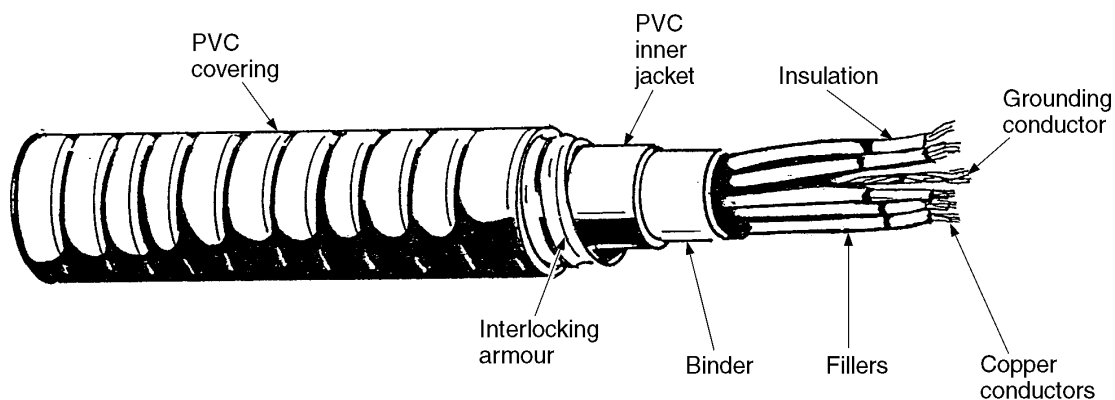


Figure 4—TECK 90 cable construction

Aluminum-sheathed cable (ASC)

In ASC, a seamless aluminum sheath protects the conductors. They have either a smooth or a corrugated finish. The corrugated type is commonly referred to as *corflex*. It also has a PVC jacket over the outer sheath that makes it more adaptable to adverse conditions. See Figure 5.

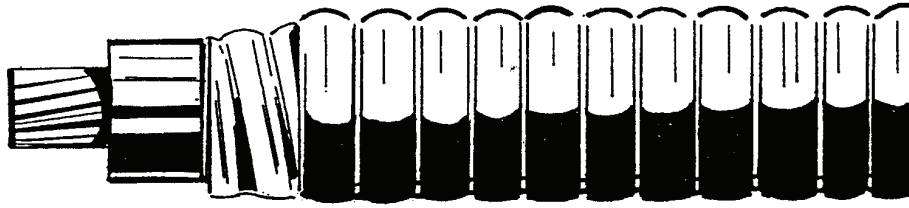


Figure 5—Corflex ASC

Aluminum-sheathed cables are more commonly used in industrial applications involving circuits of 600 V to 5000 V.

Mineral-insulated cable

Mineral-insulated (MI) cable has a magnesium oxide filler between the internal uninsulated conductors and the outer metallic (commonly copper) sheath, which makes it fire-resistant. See Figure 6. Because of this unique construction, a crushing blow to the cable changes the shape of not only the outer sheath but also the inner insulation and conductors. This allows the cable to withstand severe physical abuse without failing.

MI cable is often referred to as *Pyrotenax*, which is the name used by a major manufacturer.

Lightweight mineral-insulated (LWMI) cable is available for circuits up to 300 V. The other type, MI, is certified for 600 V.

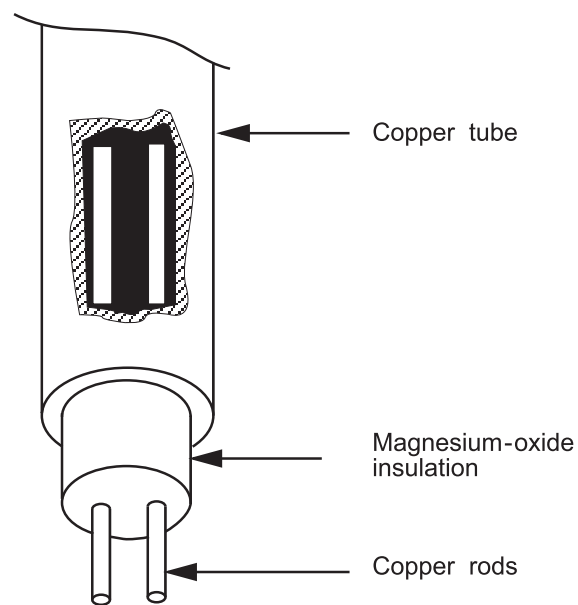


Figure 6—Mineral-insulated cable

MI cable has been used for years in applications where the conductors may be susceptible to mechanical damage, moisture or higher temperatures. Since the internal conductors are uninsulated, it requires special connection techniques. These techniques involve unique *termination kits*.

Neutral supported cable

Neutral supported cable (NSC) is commonly used for overhead services involving secondary distribution on private property. It typically has one, two or three insulated (usually aluminum) conductors wrapped about a bare neutral conductor (called the *messenger*). See Figure 7.

The most common types of neutral supported cable are:

- NS 75 rated at 75 °C
- NS 90 rated at 90 °C

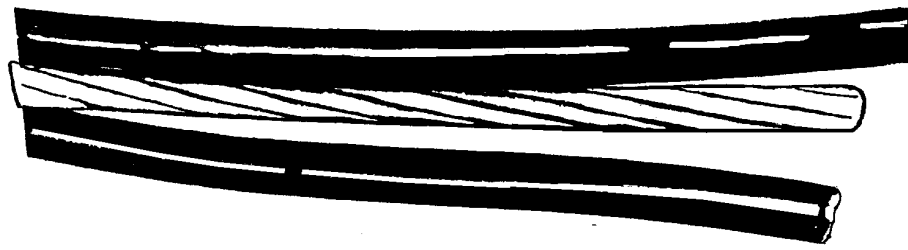


Figure 7—Neutral supported cable

Single-phase, three-wire, 120/240 V overhead distribution uses triplex NSC. Three-phase, four-wire feeders use quadruplex NSC.

Flexible cord or cable

A single conductor is made flexible by incorporating many fine strands of wire. When two or more flexible wires are run together in a single jacket, a *flexible cord* or *cable* is produced. Flexible cords are generally not allowed for permanent wiring. They are used for pendant and portable equipment that usually have attachment plugs. Various types of flexible cords and their conditions of use are listed in the CEC.

Range and dryer cable is Type DRT. It is a twisted assembly of four coloured insulated conductors (including ground) inside a thermoplastic jacket. It is rated at 300 V maximum, comes in lengths up to 2 m, and has a permanently attached plug. Common cable sizes are No. 10, No. 8, No. 6 and No. 4 AWG copper.

Heater cord is used for connection to portable heating equipment. This cord is available in two-, three- or four-conductor form, and is usually insulated with rubber and asbestos. Sometimes another cotton braid or polychloroprene jacket is used. The maximum voltage rating of this cable is 300 V. It ranges in size from No. 18 to No. 14 AWG. Types HPD, HPN and SHJO are common types listed in the CEC.

General-service cords are used for attachment to portable devices subject to hard and extra-hard usage. Type SJOW (300 V) and Type SOW (600 V) are for outdoor use. Service cords are normally available in three- and four-conductor assemblies. They typically range in size from No. 18 to No. 4 AWG. Service cords are sometimes referred to as *cabtire*.

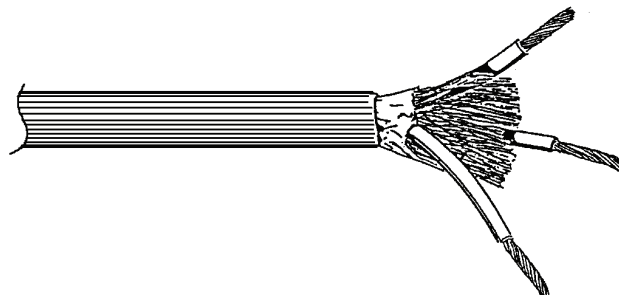


Figure 8—Type SJOW service cord

Power-supply cables are used for larger current devices up to 25 kV. This cable is generally available from single- to six-conductor form with a range of No. 12 AWG to 500 kcmil.

A portable power-supply cable is shown in Figure 9.

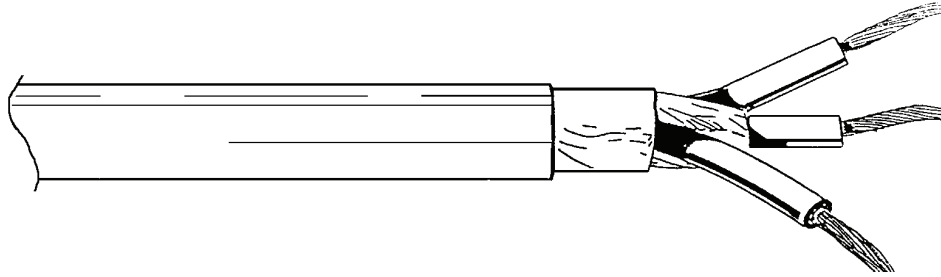


Figure 9—Portable power cable

Flat conductor cable

Flat conductor cable (FCC) is a relatively new system of branch circuit wiring used to supply floor outlets in office areas of commercial buildings. Figure 10 illustrates its use. It is commonly rated at 15 A or 20 A, single-phase, two-wire with ground, with a maximum of 150 V between conductors and ground.

Type FCC is referred to as an *under-carpet* wiring system.

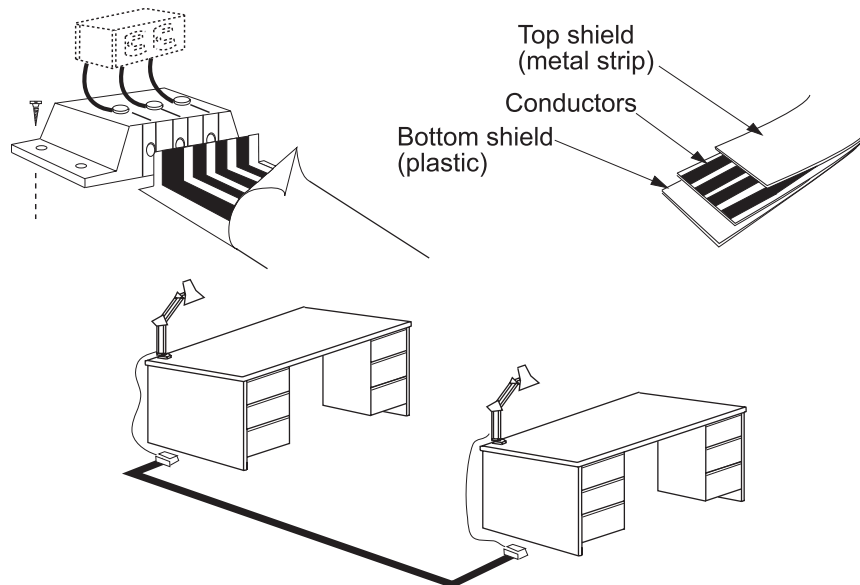


Figure 10—Flat conductor cable use

Bus bar applications

The use of bare bus bars is somewhat restricted. They are not commonly used indoors and are generally found only in older generating stations and electrical vaults. Tubular aluminum bus however, is very popular for outdoor distribution in electrical utility switchyards and substations. Tubular bus is preferred for its light weight and rigidity.

Bus bars may be applied to many different types of distribution equipment. Some of the more common ones are described here.

Distribution panels

Individual circuits are connected at panelboards, which also protect the circuits. The bus bars are convenient for attaching the circuit breakers that feed smaller circuits. An example is shown in Figure 11.

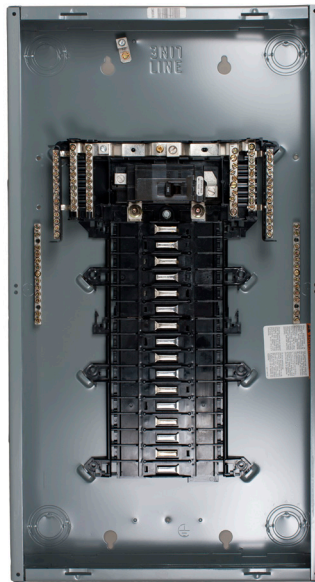


Figure 11—Distribution panel

The panel's ampacity is directly related to the size of the bus bars it contains.

Splitters

As the name implies, a *splitter* is used to divide a service into smaller subfeeds. Figure 12 shows a typical splitter gutter.



Figure 12—Splitter gutter

Splitters have electrical ratings based on the sizes of bus bars in them. Typical ratings are 400 A, 800 A, 1200 A and 1600 A. For example, a 1200 A main service may be split into three 400 A sub-feeds.

Busways

Busway or *bus duct*, as it is sometimes called, is a system assembled from prefabricated sections. The sections provide plug-in openings at regular intervals for switches and tap-off devices. Because it is flexible and neat, it is ideal for factory production areas and school shop classrooms. See Figure 13.

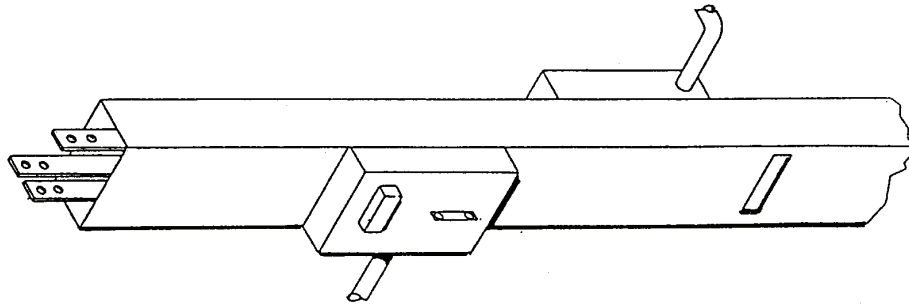


Figure 13—Typical plug-in bus duct

Motor control centres

A motor control centres (MCC) is a mechanical grouping of combination motor-starters. It contains an internal bus bar network. See Figure 14.

This bus network provides power to modular, plug-in motor-starter units.

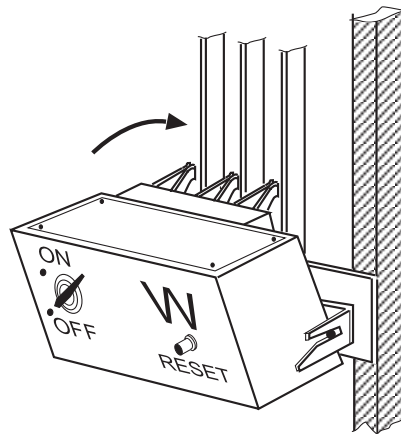


Figure 14—Motor control centre



Now do Self-Test 16 and check your answers.

Self-Test 16

1. Describe briefly the meaning of the term *service conductors*.

2. The CEC classifies low voltage as any value from _____ V to _____ V inclusive.

3. List two control-circuit applications that are classified as extra-low voltage.

4. Communication and signal circuits are generally extra-low voltage, and use special _____ conductors.

5. In which types of building construction is NMSC almost always used?

6. What is the maximum voltage rating for NMSC?

7. In Type NMD-90, what does the 90 stand for?

8. What is the purpose of the bare wire in NMSC?

9. In *Type* ACL90, what does the L stand for?

10. What is TECK 90 cable?

11. What hazard is associated with PVC-jacketed cables?

12. What are the two constructional types of aluminum-sheathed cables (ASC)?

13. What jacket material is used for corrosion-resistant cables?

14. Why is MI cable considered a fire-resistant wiring product?

15. What is necessary when terminating MI cable?

16. What is the main use of NS cable?

17. When using NS cables, what is a messenger?

18. What is Type DRT cable used exclusively for?

19. What is a general service cord commonly used for?

20. Bus bars usually determine the _____ rating of distribution panels.

21. Bus bars are usually made from which two common materials?

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

Learning Task 17:

Measure and describe the sizing of conductors

Conductor sizes – mils

Because wire cross-sections are rather small, it is convenient to use a small unit of measurement to express wire size. The long-accepted unit is one-thousandth ($\frac{1}{1000}$) of an inch and is known as a mil (an abbreviation of milli-inch).

Electrical wire sizes are based on the cross-sectional areas of the conductors. The end view of a straight cut through a wire is usually a circle; the size system is based on the area of that circle.

An important unit of wire size is the circular mil. One circular mil is the cross-sectional area of a wire with a diameter of one mil. This is the unit most used to compare wire sizes. The circular mil is abbreviated cmil, C.M. or CM. CM will be used throughout this Learning Task.

Using the concept of the circular mil makes it simple to express the size of any wire of known diameter: the cross-sectional area is equal to the square of wire diameter (in mils).

For example, a wire with a diameter of 0.030 inch (30 mil) has a cross-sectional area of 900 CM ($30^2 = 900$).

This method of calculating a conductor's area is unique to the electrical industry. For larger wires, you may see either of the units MCM or kCM in textbooks:

- M is the Roman numeral for one thousand, so the unit MCM is sometimes used, where 1 MCM = 1 CM $\times$ 1000.
- The metric system and the Canadian Electrical Code (CEC) use the metric symbol k to stand for one thousand, so that 1 kCM = 1000 CM.

Some conductors, such as bus bars, have rectangular cross-sections. Their sizes are also expressed as areas of cross-section, calculated by multiplying the thickness and width of the bar together. These areas are expressed in *square mils*. Cross-sectional areas of one circular mil and one square mil are shown in Figure 1.

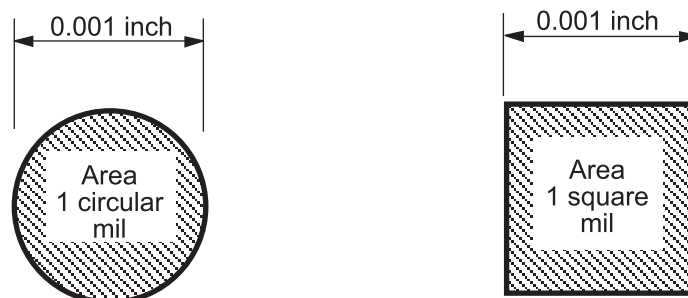


Figure 1—Cross-sectional areas of conductors

Example 1: Calculate circular mil area (CMA)

Calculate the CMA of a conductor $\frac{1}{2}$ " in diameter.

Step 1: Convert $\frac{1}{2}$ " to a decimal fraction.

$$\frac{1}{2}" = 0.5000"$$

Step 2: Convert 0.5000" to mils by multiplying by 1000.

$$0.5000 \times 1000 = 500 \text{ mils}$$

Step 3: Find circular mil area by squaring mil diameter.

$$\begin{aligned} \text{CM area} &= 500^2 \text{ CM} \\ &= 250\,000 \text{ CM} \\ &= 250 \text{ MCM or kCM} \end{aligned}$$

Example 2: Calculate square mil area (SMA)

Calculate the square mil area of a bus bar $\frac{1}{4}$ " thick and 2" wide.

Step 1: Convert $\frac{1}{4}$ " to a decimal fraction.

$$\frac{1}{4}" = 0.250"$$

Step 2: Convert 0.250" and 2.0" to mils by multiplying by 1000.

$$\begin{aligned} 0.250 \times 1000 &= 250 \text{ mils} \\ 2.00 \times 1000 &= 2000 \text{ mils} \end{aligned}$$

Step 3: Square mil area = thickness $\times$ width

$$\begin{aligned} &= 2000 \times 250 \text{ square mils} \\ &= 500\,000 \text{ square mils} \end{aligned}$$

Example 3: Convert circular mils to square mils.

The factor used to convert CMA to square mil area is 0.7854. This is found by using the formula for area A of a circle of radius r and diameter d.

$$\begin{aligned} A &= \pi r^2 \text{ where } \pi = 3.1416 \\ &= \pi (d/2)^2 \\ &= \pi d^2/4 \end{aligned}$$

But,

$$\begin{aligned} 3.1416 \div 4 &= 0.7854 \\ \therefore A &= 0.7854d^2 \end{aligned}$$

Area of a square with side length d is d^2 .

$\therefore$ Each circular mil is equivalent to 0.7854 square mils.

Note that Figure 1 shows that a circle of diameter d has a smaller area than a square of side length d.

To convert a CMA to SMA, multiply the CMA by 0.7854.

$$\text{SMA} = \text{CMA} \times 0.7854$$

What is the square mil area of a conductor 25 mil in diameter?

$$\begin{aligned}\text{CMA} &= (25 \text{ mil})^2 \\ &= 625 \text{ CM}\end{aligned}$$

$$\begin{aligned}\text{SMA} &= \text{CMA} \times 0.7854 \\ &= 625 \times 0.7854 \text{ square mils} \\ &= 490.87 \text{ SM} = 491 \text{ SM}\end{aligned}$$

(Since the circular mil area is generally quite a large number, round off the decimals.)

Example 4: Convert square mils to circular mils

Transposing the formula for finding SMA and solving for CMA:

$$\text{CMA} = \text{SMA} \div 0.7854$$

That is, to convert square mil area to circular mil area, divide the area in square mils by 0.7854.

Calculate the number of circular mils in a bus bar $\frac{1}{8}$ " thick by 1" wide and 6" long.

Step 1: Convert the cross-sectional dimensions to mils.

$$\begin{aligned}\frac{1}{8}" &= 125 \text{ mils} \\ 1" &= 1000 \text{ mils}\end{aligned}$$

Step 2: $\text{SMA} = 125 \times 1000 = 125\,000 \text{ SM}$

Step 3: $\begin{aligned}\text{CMA} &= \text{SMA} \div 0.7854 \\ &= 125\,000 \div 0.7854 \text{ CM} \\ &= 159\,154 \text{ CM}\end{aligned}$

Stranded conductors

Example 5

Not all wires are single conductors; some are made up of many conductors (Figure 2). The most common numbers of conductors in stranded configurations are 7, 19, 37, 61, 91 and 127.

To find the total circular mil area of stranded conductors, find the CMA of one conductor and then multiply this by the total number of strands.

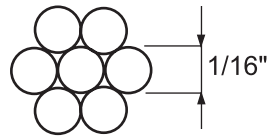


Figure 2—A stranded conductor

Find the total CMA of the stranded conductor in Figure 2.

Step 1: Strand diameter = $\frac{1}{16}$ " = 0.0625" = 62.5 mils

Step 2: Circular mil area for one strand = $(62.5)^2$ CM
= 3906.25 CM

Step 3: The conductor in Figure 2 has seven strands.

$$\begin{aligned}\text{Total CMA} &= 7 \times 3906.25 \text{ CM} \\ &= 27\,343 \text{ CM}\end{aligned}$$

American wire gauge

Wires are manufactured in sizes numbered according to what was formerly known as the Brown & Sharpe (B&S) gauge but is now known as American Wire Gauge (AWG).

Special measuring gauges (Figure 3) are used to determine actual physical wire size.

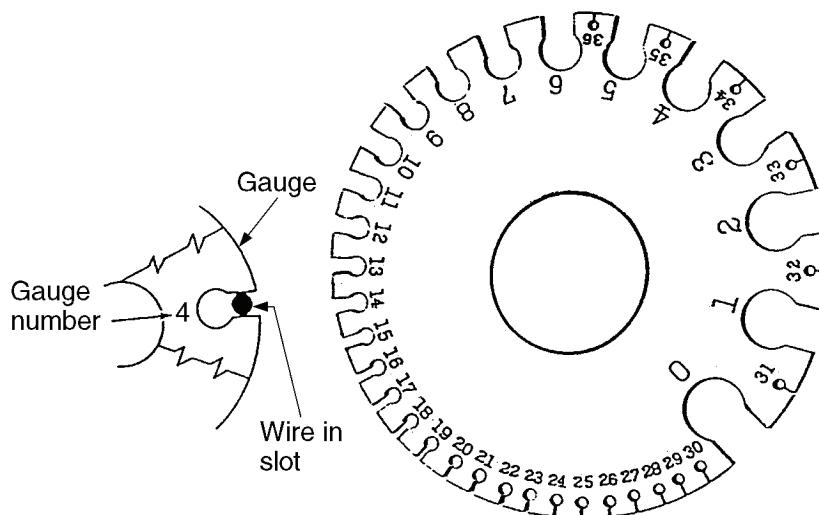


Figure 3—Wire gauge

This gauge is used to measure only solid wire conductors. The outer edge of the gauge contains numbered slots. The smallest slot into which the wire will fit is the AWG number of the wire. Table 1 shows some of the AWG numbers with the cross-sectional wire sizes they represent.

For special purposes, wire is manufactured as small as No. 50 and as large as 0000 (also referred to as 4/0). The smallest wires are used in the windings of electric motors and similar equipment.

Wire and cable for buildings are made in even gauge sizes, such as Nos. 14, 12, 10, 8. Odd gauge sizes, like Nos. 15, 13, 11, 9, etc., are not used for wiring buildings because there is not enough difference in current-carrying capacity to make production of these odd sizes worthwhile. They are reserved for critical current applications such as motors and transformers.

Refer to the wire gauge table as you read through the following notes and examples. At first, the wire sizes may seem a bit confusing, but if you use certain rules of thumb your task will be much easier.

Table 1: AWG sizes

AWG gauge no.	Diameter in mils	Area in cm	AWG gauge no.	Diameter in mils	Area in cm
0000	460	211 600	21	28.5	810
000	410	167 800	22	25.4	642
00	365	133 100	23	22.6	510
0	325	105 500	24	20.1	404
1	289	83 690	25	17.9	320
2	258	66 370	26	15.9	254
3	229	52 640	27	14.2	202
4	204	41 740	28	12.6	160
5	182	33 100	29	11.3	126.7
6	162	26 250	30	10.0	100.5
7	144	20 820	31	8.93	79.7
8	128	16 510	32	7.95	63.2
9	114	13 090	33	7.08	50.1
10	102	10 380	34	6.31	39.8
11	91	8234	35	5.62	31.5
12	81	6530	36	5.00	25.0
13	72	5178	37	4.45	19.8
14	64	4107	38	3.96	15.7
15	57	3257	39	3.53	12.5
16	51	2583	40	3.15	9.9
17	45.3	2048	42	2.50	6.3
18	40.3	1624	44	1.97	3.9
19	35.9	1288			
20	32.0	1022			

** The larger the AWG number, the smaller the diameter and cross-section area of the wire.*

Example 1

No. 8 AWG = 128 mils (or 16 384 CMA)

No. 16 AWG = 51 mils (or 2601 CMA)

The larger the AWG number, the greater the resistance per unit length of the wire.

Example 2

No. 4 AWG = 0.0815 Ω /100 m

No. 7 AWG = 0.163 Ω /100 m

The ratio of the cross-section (in circular mils) of one gauge number to that of the next *higher* gauge number is 1.26.

Example 3

No. 11 AWG = 8 234 CM

No. 12 AWG = 6 530 CM

$$\frac{8234}{6530} = 1.26$$

The cross-sectional area (CMA) is approximately *halved* or *doubled* every *three* gauge numbers.

Example 4

No. 10 AWG = 10.380 CM

No. 13 AWG = 5 178 CM

$$\frac{5178}{10380} = \frac{1}{2} \text{ or } \frac{10380}{5178} = 2$$

For rough estimates of cross-sectional area and resistance, you do not need the AWG table. Use the previous notes and memorize *approximate* specifications for AWG No. 10.

No. 10 AWG = 100 mils

CMA = 10 000 CM

R = 1 Ω /1000 ft.

Example 5

To estimate the cross-sectional area and the resistance of 1000 feet of No. 17 wire, we use the following reasoning:

- No. 17 AWG is 3 sizes removed from a No. 20 and therefore has twice the CMA of a No. 20.
- No. 20 AWG is 10 sizes removed from a No. 10 and therefore has one-tenth the CMA of No. 10.

$\therefore$ CMA of No. 17 is $2 \times 0.1 \times 10\,000 \text{ CM} = 2000 \text{ cm}$.

- Resistance varies inversely with CMA.

$\therefore$ Resistance of No. 17 is $0.5 \times 10 \times 1 = 5 \text{ } \Omega$ /1000 ft.



Now do Self-Test 17 and check your answers.

Self-Test 17

1. A mil is one-thousandth of an inch.
 - a. True
 - b. False

2. A circle with 1 mil diameter has an area of 1 circular mil.
 - a. True
 - b. False

3. A circular mil has more area than a square mil.
 - a. True
 - b. False

4. MCM means 1000 square mil.
 - a. True
 - b. False

5. Square mil area divided by 0.7854 equals circular mil area.
 - a. True
 - b. False

6. Circular mil area multiplied by 0.7854 equals square mil area.
 - a. True
 - b. False

7. Calculate how many mils are in:
 - a. 0.65 inch _____
 - b. 0.175 inch _____
8. A wire has diameter $\frac{3}{16}$ ". Find its diameter in mils.

9. What is the diameter in mils of a wire with an area of 16 900 circular mils?

10. A conductor is $\frac{1}{8}" \times \frac{3}{8}"$ in cross-section. Find its circular mil area (CM).

11. Find the cross-sectional area in circular mils of a conductor that is 1 inch square.

12. The diameter of No. 14 wire is 64 mils. What is its area in CM and in SM?

13. If a ribbon-shaped conductor is 120 mils thick and has a cross-sectional area of 46 000 CM, what must be the width of the section?

14. A square conductor has a CMA of 40 000. Find its area in square mils.

15. A copper bar is $\frac{7}{16}" \times \frac{1}{2}"$ in cross-section. Find its:

a. square mil area _____

b. CMA _____

16. A copper ribbon is $\frac{3}{4}" \times \frac{1}{4}"$ in cross-section. Find its:

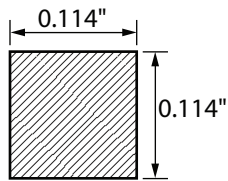
a. square mil area _____

b. CMA _____

17. Find the CMA and the SMA of a $\frac{7}{8}" \times \frac{1}{8}"$ rectangular bar.

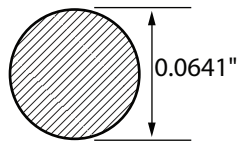
18. Find the SMA and CMA of a $2" \times \frac{1}{4}"$ copper bus bar.

19.



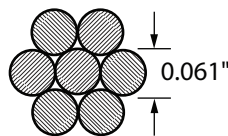
- a. Convert the micrometer reading shown in this figure to mils. _____
- b. Calculate the circular mil and square mil areas of the conductor. _____

20.



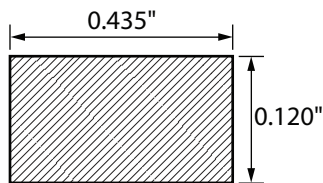
- a. Convert the micrometer reading shown in this figure to mils. _____
- b. Calculate the circular mil and square mil areas of the conductor. _____

21.



- a. Convert the micrometer reading shown in this figure to mils. _____
- b. Calculate the circular mil and square mil areas of the conductor. _____

22.



- a. Convert the micrometer readings shown in this figure to mils. _____
- b. Calculate the circular mil and square mil areas of the conductor. _____

23. The _____ table lists various conductor sizes based on their cross-sectional area.

24. As the gauge number for a wire increases from No. 1 to No. 20, does the wire size get smaller or larger?

25. In the AWG system, the cross-sectional area of a wire is measured in:

- a. square millimetres
 - b. square metres
 - c. circular millimetres
 - d. circular mils
-

26. Successive wire size areas in the AWG table have a ratio of _____ to 1.

27. What is the relationship between the area of a No. 1 wire and a No. 4 wire in the AWG table?

28. How would you measure a solid wire conductor using an American Wire Gauge?

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

Learning Task 18:

Calculate the resistance of conductors

A material that allows electrical current (free electrons) to flow with relative ease is known as a *conductor*. The ideal electrical conductor is a material that will carry the greatest amount of current with the least temperature rise. In practice, cost, strength and ease of use are important criteria for selecting a conductor material.

For example, silver is a better conductor than copper, but copper is more widely used because it is less expensive. Aluminum, with relatively low tensile strength, is used as a conductor where weight is a major consideration, such as in high-tension lines with long spans between supports. Usually these lines are stranded cables with small, steel-wire cores added to strengthen the aluminum cable.

The ability of a material to conduct electricity depends on its dimensions. Conductors may be in the form of bars, tubes or sheets, but the most common conductors are in the form of wire. Many sizes of wire are used, from the fine, hairlike wire used in the coils of sensitive measuring instruments to the large bus bar sizes used for carrying high current in electric power-generating plants. To protect it, wire is usually covered with an insulating material. This material may be rubber, cotton, plastic or enamel. These coverings protect against short circuits and leakage and are insulators.

Resistance and conductance

When current flows in an electric circuit, the free electrons “collide” not only with each other but also with the bound electrons of the atoms in the circuit. These collisions impede the progress of the free electrons, and the effect is called the resistance (R) of the circuit. This opposition to charge flow (current) is measured in the basic unit of *ohms*. The unit symbol used for ohms is Ω , the Greek letter omega.

A circuit has a resistance of 1 Ω whenever a potential difference of 1 V is applied to the circuit and a current of 1 A flows:

$$1\Omega = \frac{1\text{V}}{1\text{A}}$$

As with other units, metric prefixes are used:

$$1000\Omega = 1\text{ k}\Omega \text{ (1 kilohm)}$$

$$1\,000\,000\Omega = 1\text{ M}\Omega \text{ (1 megohm)}$$

Thus:

$$470\,000\Omega \text{ can be written as } 470\text{ k}\Omega$$

$$22\,000\,000\Omega \text{ can be written as } 22\text{ M}\Omega$$

Small resistance values may be expressed in milliohms (m Ω). For example, 0.030 Ω can be written as 30 m Ω , but the decimal form 0.030 Ω is also acceptable.

Resistance is similar in some ways to friction in mechanical systems. Just as friction may be undesirable, since it causes loss of efficiency (mechanical energy is dissipated as waste heat), so resistance can be detrimental, since it converts electrical energy into waste heat. Just as mechanical bearings should have low friction, conductors should have low resistance to minimize this energy waste.

Sometimes friction is desirable (for example, in the braking system of a car), and so is resistance. For example, the heat produced by current flowing through the resistance of a heating element in an appliance such as a toaster or iron is very beneficial. Such heating elements are made to have a higher resistance by selecting a suitable material and by changing certain other factors that affect resistance.

Factors affecting resistance

The resistance of a wire depends on four main factors:

- Natural resistance (*resistivity* or *specific resistance*, labelled K) of the material
- Length of the wire
- Cross-sectional area of the wire
- Temperature

Resistivity is often expressed in ohms/mil-foot, which is the resistance of a piece of wire 1 foot long and 1 mil in diameter, as shown in Figure 1.

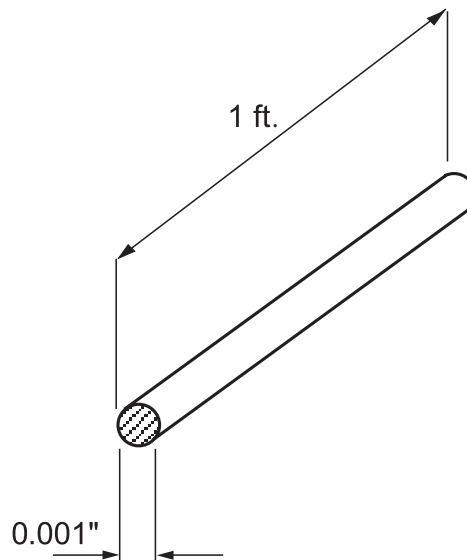


Figure 1—1 mil-foot of wire

For a given temperature, the equation below shows the relationship of these factors:

$$R = \frac{K \times L}{CMA}$$

where:

- K = resistivity of the material in ohms per mil-foot
- L = length of the wire in feet
- CMA = cross-sectional area of the wire in circular mils

This equation expresses that resistance:

- Is directly proportional to length (more collisions for a longer wire).
- Is inversely proportional to cross-sectional area (a smaller cross-section will increase the current density and the number of collisions that occur).
- Depends upon the type of material, as indicated by the resistivity K.

Table 1 gives the resistivities at room temperature of common conductors, semiconductors and insulators.

Table 1: Resistivities (K)

K = ohms per mil-foot at 20°C	
Aluminum	17
Brass	42
Cadmium, bronze	12
Copper	10.4
Copper-clad aluminum (20% Cu)	15.2
Copperweld	26–34
Iron	60
Nichrome	600
Silver	9.6
Steel	75
Tungsten	33

Sample problems

Here are several worked examples that use the equation $R = \frac{K \times L}{CMA}$.

Example 1: Find the resistance of 800 feet of No. 16 copper wire.

From AWG Table 1, circular mil area of No. 16 wire is 2583 CM.

$$\begin{aligned} R &= \frac{K \times L}{CMA} \\ &= \frac{10.4 \times 800}{2583} = 3.22 \, \Omega \end{aligned}$$

Example 2: What diameter must copper wire have so that 1 mile of it has a resistance of 0.196 Ω ?

One mile equals 5280 feet.

$$\begin{aligned} CMA &= \frac{KL}{R} \\ CMA &= \frac{10.4 \times 5280}{0.196} = 280\,000 \\ D &= \sqrt{280\,000} = 529 \text{ mils} \\ &= 0.529 \end{aligned}$$

Example 3: Find the length in kilometres of a copper wire with a CMA of 4110 CM and a resistance of 25 Ω .

$$\begin{aligned} L &= \frac{R \times CMA}{K} \\ &= \frac{25 \times 4110}{10.4} = 9880 \text{ feet} \end{aligned}$$

$$\begin{aligned} 1 \text{ m} &= 3.281 \text{ feet} \\ \text{Length} &= 9880 \div 3.281 = 3011 \text{ m} \\ &= 3.011 \text{ km} \end{aligned}$$

Example 4: What CMA of iron wire would have the same resistance as the wire in Example 1, if the length remains the same?

Using Table 1, resistivity of iron is 60 Ω /mil-ft.

$$\begin{aligned} CMA &= \frac{KL}{R} \\ &= \frac{60 \times 800}{3.22} = 14\,906.8 \text{ CM} \end{aligned}$$

Example 5: Calculate the resistance of 200' of $\frac{3}{4}" \times \frac{5}{8}"$ copper bus bar.

$$\begin{aligned} \text{SMA} &= \frac{3}{4}" \times \frac{5}{8}" \\ &= 0.750" \times 0.625" \\ &= 750 \text{ mils} \times 625 \text{ mils} \\ &= 468\,750 \text{ SM} \end{aligned}$$

$$\text{CMA} = 468\,750 \div 0.7854 = 596\,829 \text{ CM}$$

$$R = \frac{KL}{\text{CMA}} = \frac{10.4 \times 200}{596\,829} = 0.0035 \, \Omega$$

Temperature effects on resistance

Designers of electrical apparatus pay close attention to the effects of temperature changes in conductors because the resistance of a conductor varies with temperature. In the temperature range at which electrical equipment operates, resistance increase is practically proportional to temperature increase.

The resistance of each type of conductor changes by a different amount as temperature changes. A factor called the *temperature coefficient of resistance* has been worked out for each type of conductor.

The temperature coefficient of resistance is the percentage of resistance change per degree of temperature change from 20°C.

For example, the temperature coefficient of resistance of copper is 0.003 93.

- That is, for every degree the temperature of copper rises above 20°C, the resistance increases by 0.393 of 1 percent of its value at 20°C.
- Also, as the temperature decreases, the value of the resistance of copper will decrease 0.393 of 1 percent for every degree below the resistance at 20°C.

Table 2 gives temperature coefficients for common materials. Note that most are positive temperature coefficients (PTC). This means that an increase in temperature causes a rise in resistance. Carbon, semiconductors and most insulators have a negative temperature coefficient (NTC). This indicates that a rise in temperature causes a drop in resistance. In these materials, the current is carried by electrons freed from the valence orbits by heat. Raising the temperature frees more electrons from the valence orbits, which increases the availability of current carriers.

Table 2: Temperature coefficients

Temperature coefficients per degree Celsius per ohm at 20°C			
Aluminum	0.0039	Manganin	0.000 000
Brass	0.0020	(84% Cu, 12% Mn, 4% Ni)	
Carbon	−0.0005	Mercury	0.000 88
Constantan (60% Cu, 40% Ni)	0.000 002	Nichrome	0.0004
		Nichrome II	0.000 16
Copper	0.003 93	Nickel	0.006
Gold	0.0034	Platinum	0.003
Iron	0.0050	Silver	0.0038
Lead	0.0043	Tungsten	0.0045

Note that manganin has a temperature coefficient of zero. This means that its resistance is independent of temperature. Materials such as this are said to have *constant resistance*. Because the values of their temperature coefficients are so low, mercury, nichrome and nichrome II are also classed with manganin as having constant resistance.

Change in resistance caused by a temperature change is calculated for a given material using the following equation:

$$R_c = R_o \times \alpha \times \Delta T$$

where:

R_o = original resistance

R_c = change in resistance

α = temperature coefficient

ΔT = temperature change

Also, new resistance (R_n) = original resistance + resistance change

$$R_n = R_o + R_c$$

Sample problems

Example 6: The resistance of a copper coil is 125 ohms at 15°C. What would be the resistance of the coil at 25°C?

Step 1

$$\begin{aligned} R_c &= R_o \times \alpha \times \Delta T \\ &= 125 \times 0.00393 \times 10 = 4.91 \, \Omega \end{aligned}$$

Step 2

$$\begin{aligned} R_n &= R_o + R_c \\ &= 125 + 4.91 = 129.91 \, \Omega \end{aligned}$$

Example 7: What is the resistance of 250 feet of No. 12 aluminum wire at 90°C?

Step 1: Resistivity of aluminum is 17 Ω /mil-ft.

$$\begin{aligned} R_o &= \frac{K \times L}{CMA} \\ &= \frac{17 \times 250}{6530} = 0.6508 \, \Omega \text{ at } 20^\circ\text{C} \end{aligned}$$

Step 2: Resistance change due to 70°C temperature rise

$$\begin{aligned} R_n &= R_o \times \alpha \times \Delta T \\ &= 0.6508 \times 0.0039 \times 70 = 0.1777 \end{aligned}$$

Step 3:

$$\begin{aligned} R_n &= R_o + R_c \\ &= 0.6508 + 0.1777 = 0.8285 \, \Omega \end{aligned}$$



Now do Self-Test 18 and check your answers.

Self-Test 18

1. If two wires have the same length and cross-sectional area, but one is copper and the other is aluminum, which has the lower resistance?

2. How would the resistance of a copper wire be affected if its:

- a. length were doubled?

- b. cross-sectional area were doubled?

- c. length and cross-sectional area were doubled?

3. In simple terms, explain the difference between a positive and a negative temperature coefficient of resistance.

4. Find the resistance of the following copper conductors:

Diameter	Length	Resistance
a. 0.008"	128 feet	
b. 0.12"	2880 feet	
c. 0.05"	750 feet	

5. Find the length, in feet, of the following aluminum conductors:

Resistance	Area	Length
a. 2.5 ohms	8500 CM	
b. 0.51 ohms	6600 CM	
c. 1.5 ohms	2040 CM	

6. What is the resistance of a copper wire that is 250 feet long and has a diameter of 15 mil?

7. What is the resistance of 750 feet of copper wire if it has a diameter of 0.02 inches?

8. How many miles (and kilometres) of copper wire, 0.125 inches in diameter, will it take to make up a resistor of 10 ohms?

9. What is the resistance of a two-wire service run from an overhead line that is 200 feet away from a house? The service size is No. 8 AWG copper.

10. A copper wire has a resistance of 12 ohms. What is the approximate resistance of an aluminum wire of the same length and diameter?

11. The resistance of a coil of copper wire at 0°C is 8.06 Ω . What will its resistance be at 60°C? (Temperature coefficient = 0.004)

12. The resistance of a transformer at 20°C is 12.83 Ω . What will its resistance be at 90°C? (Temperature coefficient = 0.004)

13. The resistance of a coil wound with iron wire is 200 Ω at 20°C. What is its resistance at 80°C? (Temperature coefficient = 0.005)

14. The resistance of a copper generator coil is 0.10 Ω at 20°C. After running on full load, the coil resistance changes to 0.114 Ω . What was the temperature rise in the coil? (Temperature coefficient = 0.004)

15. A carbon lamp has a cold resistance at 20°C of 260 Ω and a hot resistance of 200 Ω . Find the operating temperature of this carbon lamp. (Negative temperature coefficient = -0.0003)

16. A tungsten lamp bulb has a cold resistance of 40 Ω and is heated to 1000°C above room temperature when lit. Find the hot resistance of this lamp. (Temperature coefficient = 0.0045).

17. If a No. 10 copper wire has a resistance of approximately 1 ohm per 1000 feet, what is the estimated approximate resistance of 1000 feet of No. 7 copper wire?

18. If the resistance of a length of copper wire is 10 ohms, an aluminum wire of the same gauge and length has a resistance of:

- a. 1.64 ohms
 - b. 15.625 ohms
 - c. 16.4 ohms
 - d. 64 ohms
-

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

Learning Task 19:

Determine the ampacity of various types of conductors

Ampacity refers to the rated current carrying capacity of a conductor. Exceeding the current rating of a conductor can result in excessive heating (I^2R), which may harm the insulation and perhaps even cause a fire.

The allowable ampacity of a conductor varies according to:

- The type of conductor material (copper or aluminum)
- The size of conductor (in AWG size)
- The temperature rating of the insulation used on the conductor
- Whether the conductor is installed in free air, raceway or cable
- The surrounding air (ambient) temperature
- The number of conductors in contact with each other (ie: in a conduit or cable and where conductors are placed close to others)

There are many different factors involved for sizing conductors and they will be discussed while studying Section 4 of the Canadian Electrical Code. For the purposes of this Learning Task, the focus will be on the allowable ampacity of specific sizes of conductors, and not on the equipment they are supplying.

The ampacity rating of a conductor changes with its composition. For example, copper has greater conductivity than aluminum and can therefore conduct more current for a given size. Details of various conductor ampacities are listed in CEC Section 4 and Tables 1, 2, 3, 4, 12 and 36.

Conductor ampacities (CEC Tables 1 to 4)

To determine ampacity of a conductor:

1. Identify its composition. Is it copper or aluminum?
2. Identify its method of installation. Is it in free air or in a raceway/cable assembly?
3. Know its insulation type and temperature rating. Is it TW, RW75 or R90, etc.?
4. Use this information to refer to CEC Tables 1, 2, 3 and 4.

Example 1: What is the allowable ampacity of a No. 8 TW copper conductor run in free air?

(**Note:** From Table 19 in the CEC, TW wire has a maximum allowable conductor temperature of 60 degrees celcius.)

1. Refer to CEC Table 1, which lists single unshielded copper conductors, rated not more than 5000 V, in free air.
2. Use Column 1 to locate the No. 8 wire size.

3. Read across to Column 2, which is for conductors with a maximum allowable conductor temperature of 60° C.

Solution: Aligning the No. 8 row with the 60° column, the allowable ampacity is 60 amperes.

Example 2: What is the allowable ampacity of a No. 8 R90 aluminum conductor run in free air?

1. Since the conductor is aluminum in free air, refer to CEC Table 3.
2. Look at the listing for wire size No. 8 and read across to the column with the maximum allowable conductor temperature of 90° C to get the ampacity rating.

Solution: Aligning the No. 8 row with the 90° column, the allowable ampacity is 60 amperes.

Compare CEC Table 1 (copper) and Table 3 (aluminum). Notice that for equivalent insulation temperature ratings and wire sizes above No. 14 AWG, a copper conductor has a higher ampacity than an aluminum conductor of the same AWG size.

One of the most commonly used CEC wire tables is Table 2, which deals with copper conductors installed in a raceway or cable. It is read in the same way as Tables 1 and 3.

Example 3: A three-phase motor is to be supplied with three R90 copper conductors in a single conduit. If each conductor must be rated for 90 amps, what size wire is required?

1. Since we require three copper conductors in the raceway, refer to CEC Table 2.
2. Knowing that we are using 90° insulation, read down column 4 to find ampacity of 95 amps.
3. Reading to the left, find the AWG size.

Solution: The required size is No. 4 AWG.

Flexible cord ampacity (CEC Table 12)

CEC Table 12 and Rule 4-016 specify ampacity for flexible cords.

For example, for No. 18 AWG, 3 conductor, Type ETT flexible cord (elevator travelling cable):

1. Refer to CEC Table 12 which lists allowable ampacity of flexible copper conductor cord and equipment wire.
2. Use column 1 to locate No. 18 wire size.
3. Read across to column 5 and locate the CSA designation "ETT".

Solution: Aligning the No. 18 row with the ETT column, the allowable ampacity is 5 amperes.

Neutral supported cable (CEC Table 36A & Table 36B)

CEC Rule 4-004 (5) and Tables 36A and T36B specify the ampacity of aluminum and copper neutral supported cable (NSC). The only current restriction in Table 36A and T36B is described in Note (2) at the bottom of the tables. The two types of neutral supported cable are NS75 and NS90.

Trade names of NSC are:

- Triplex (NS75 or NS90): made up of 2 insulated wires, 1 bare
- Quadraplex (NS75 or NS90): made up of 3 insulated wires, 1 bare

Example 4: Determine the maximum loading of an aluminum triplex, No. 2 AWG, NS90 NSC cable.

1. Refer to CEC Table 36A which lists the allowable ampacity for aluminum conductor neutral supported cables.
2. Use column 1 to locate No. 2 wire size.
3. Read across to column 4 and locate NS90, triplex.

Solution: Aligning the No. 2 row with the NS90, triplex column, the allowable ampacity is 165 amperes.

Example 5: Determine the minimum size of copper triplex, NS75 required to supply a 125 amp load.

1. Refer to CEC Table 36B which lists the allowable ampacity for copper conductor neutral supported cables.
2. Knowing we are using NS75 and triplex, read down column 2 to find 135 amperes.
3. Read to the left to find the AWG size.

Solution: The required size is No. 4 AWG.



Now do Self-Test 19 and check your answers.

Self-Test 19

1. List five fundamental factors that determine the allowable ampacity of a conductor.

2. What is the ampacity rating of the following single copper conductors in free air?

- a. No. 8 AWG TW _____
- b. No. 4 AWG RW90 _____
- c. 3/0 (or 000) TW75 _____
- d. 250 kcmil R90 _____
- e. 1/0 (or 0) RW75 _____

3. What is the ampacity rating of the following groups of three copper conductors in a raceway?

- a. No. 8 AWG RW90 _____
- b. No. 2 AWG TW _____
- c. No. 10 AWG TW75 _____
- d. 500 kcmil R90 _____
- e. No. 14 AWG RW75 _____

4. What is the ampacity rating of the following single aluminum conductors in free air?

- a. No. 2 AWG RW90 _____
- b. 500 kcmil R90 _____
- c. No. 10 AWG TW _____
- d. 4/0 T90 nylon _____
- e. 1000 kcmil RW75 _____

5. What is the individual ampacity rating of the following pairs of aluminum conductors in a raceway?
- a. 750 kcmil TWU _____
 - b. 3/0 TW75 _____
 - c. No. 12 AWG RW75 _____
 - d. No. 8 AWG RW90 _____
 - e. 250 kcmil RW90 _____
6. What is the difference in ampacity rating between No. 6 AWG TW copper conductors run in free air and in a raceway?
- _____
- _____
7. Determine the current rating of two No. 14 AWG STOW equipment wires run in flexible conduit.
- _____
8. What size of aluminum neutral support cable (75 degree temperature rating) would you select to feed a barn with a calculated demand of 85 A, 120/240 V?
- _____
- _____
9. Three No. 12 TW copper conductors are installed in a run of 16 mm trade size EMT. What is the rated ampacity of each conductor?
- _____

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

Learning Task 20:

Solve problems involving line loss and line drop

Line voltage drop

Because all conductors offer some resistance to current flow, some voltage is always lost between the source and the load. This is called *line voltage drop*, or simply *line drop*.

If the resistance of the conductors and the current flow in the circuit are known, then Ohm's law can be used to determine the voltage drop due to conductor resistance.

The formula is:

$$V = I \times R$$

where:

I = current flow in amperes

R = conductor resistance in ohms

V = required voltage drop

Kirchhoff's law states that the sum of all the voltage drops in a circuit is exactly equal to the applied voltage.

In Figure 1 the total line drop is 40 V.

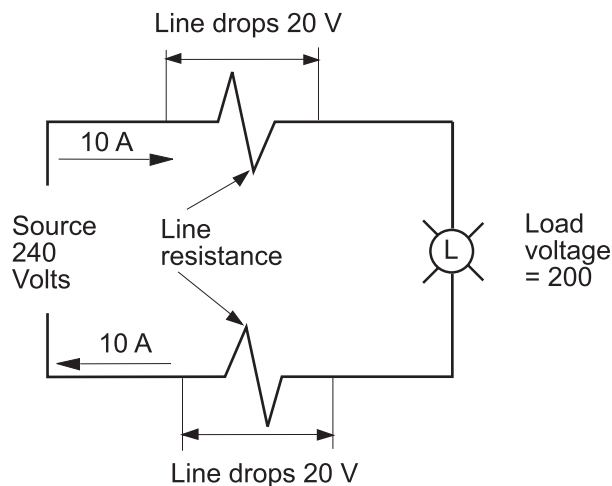


Figure 1—Two-wire circuit showing line drop

Line loss

Line loss, or *line power loss*, is the heat dissipated by the conductor as a result of the line drop and the current passing through the conductor. Line loss is a power loss and is measured in watts.

Line loss is calculated by using the electric power formulas:

Multiply the square of the current in the conductor by the resistance of the conductor.

$$P = I^2 \times R$$

Multiply the line drop voltage in the conductor by the current flowing in the conductor.

$$P = E \times I$$

Divide the square of the line drop in the conductor by the resistance of the conductor.

$$P = \frac{E^2}{R}$$

In Figure 1, the line drop is 40 V.

If the current through the conductor is 10 A, then the line (or line power) loss is:

$$\begin{aligned} P &= E \times I \\ &= 40 \text{ V} \times 10 \text{ A} \\ &= 400 \text{ W} \end{aligned}$$

Line loss and line drop calculations

When doing any line drop or line loss calculation, remember that there is voltage drop going to the load and voltage drop coming back to the supply. If a distance is given between load and supply, *double* the length to calculate total resistance, total voltage drop or total line loss.

Example 1: What is the voltage drop and line loss for a 500 m run of No. 2 copper wire carrying 60 A at 240 V?

Step 1: Draw a circuit to represent the conditions.

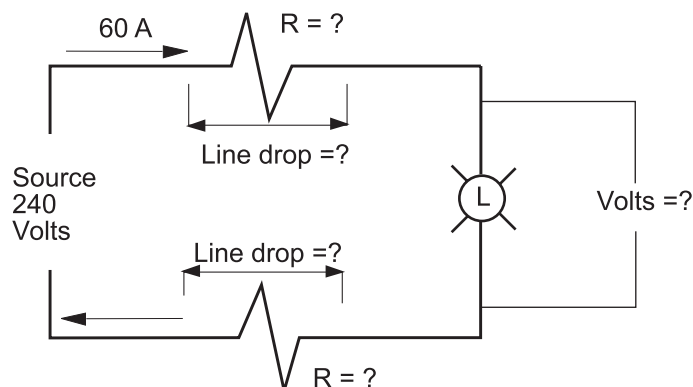


Figure 2—Circuit for Example 1

Step 2: Convert metres to feet by multiplying by 3.28.

Find the resistance of the conductors. Use Table 1 in Learning Task 17 to find the CM value for No. 2 AWG.

For one line only:

$$\begin{aligned} R &= \frac{KL}{CMA} \\ &= \frac{10.4 \times (500 \times 3.28)}{66\,370} = 0.2570 \, \Omega \end{aligned}$$

Step 3: Find the total line resistance for two lines:

$$R = 2 \times 0.2570 = 0.5140 \, \Omega$$

Step 4: Total line loss is:

$$\begin{aligned} P &= I^2 R \\ &= (60 \, \text{A})^2 \times 0.5140 \, \Omega \\ &= 1850 \, \text{W} \end{aligned}$$

Step 5: Total line drop is:

$$\begin{aligned} E &= I \times R \\ &= 60 \, \text{A} \times 0.5140 \, \Omega = 30.8 \, \text{V} \end{aligned}$$

Therefore, the voltage drop across the load, called *load volts* is:

$$\begin{aligned} E_{\text{load}} &= E_{\text{supply}} - E_{\text{drop}} \\ &= 240 \, \text{V} - 30.8 \, \text{V} \\ &= 209.2 \, \text{V} \end{aligned}$$

Line drop is usually expressed as a percentage of supply volts.

The % voltage drop for Example 1 is:

$$\frac{30.8 \, \text{V}}{240 \, \text{V}} \times 100\% = 12.8\%$$

Voltage drop formula

The formula commonly used to calculate voltage drop in two-wire copper circuits is:

$$VD = \frac{2 \times K \times L \times I}{CMA}$$

Where:

VD = voltage drop

L = one-way distance between load and supply, in feet

I = current in amperes

CMA = circular mil area

K = resistivity of copper at 20°C = 10.4

The factor of 2 takes into account that there are two wires.



Now do Self-Test 20 and check your answers.

Self-Test 20

1. A 2000-foot copper line wire is 0.204 inches in diameter. What is the voltage drop when it carries 40 A?

2. How much voltage is dropped when 3 A flows through 500 feet of copper wire 0.064 inches in diameter?

3. How much voltage is dropped when 20 A flows through 1000 feet of copper wire 0.162 inches in diameter?

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

Answer Key

Self-Test 1

1. compound
2. matter
3. protons, nucleus
4. 8
5. a. increases
6. free
7. 4
8. conductors
9. molecule
10. atom

Self-Test 2

1. increase, 16
2. fewer
3. repel, attract
4. spray painting, air filtration, xerography, smoke precipitator, sandpaper manufacturing
5. lightning, fuel handling
6. conduction, induction, friction
7. negative, positive
8. field
9. polarity
10. increase, two

Self-Test 3

1. sources
2. friction, chemical, pressure, heat, light, magnetism
3. friction
4. pressure
5. thermocouple
6. photovoltaic cell
7. electromotive force

8. magnetism or the magnetoelectric effect
9. Energy can be neither created nor destroyed.
10. photovoltaic cell

Self-Test 4

1. coulomb
2. 2
3. 600
4. resistance
5. Table for Question 5

Electrical quantity	Quantity symbol	Electrical unit	Unit abbreviation
Charge	Q	coulomb	C
Power	P	watt	W
Resistance	R	ohm	Ω
emf or PD	E	volt	V
Current	I	ampere	A

Self-Test 5

1. 300 watts
2. 48 ohms
3. 76.8 ohms
4. 750 watts
5. increases
6. increases
7. increases
8. increases, four
9. The current flowing in an electric circuit is directly proportional to the applied voltage and inversely proportional to the resistance of the circuit.
10. The power in a circuit is equal to the product of the voltage times the current in the circuit.
11. 13.8 kilovolts
12. 3.4 microamperes
13. 0.5 megavolts
14. 0.000 018 2 amperes
15. 470 000 ohms
16. 0.027 kilohms

17. 1.5 kilowatts
18. 1 500 000 milliwatts
19. 3 kilowatts
20. 200 microamperes
21. 70%
22. 5595 W & 7.5 HP
23. 9325 W & 38.9 A
24. 19 893 W & 20 HP

Self-Test 6

1. energy
2. power
3. energy
4. 0.2 kW/h
5. \$.014
6. \$5.25
7. 5.4 kW/h
8. 7.2 kW
9. 0.975 kW/h
10. \$0.068

Self-Test 7

1. pictorial
2. ladder
3. blocks, symbols
4. physical
5. pictorial
6. block
7. wiring
8. pictorial
9. one-line or block

Self-Test 8

1. load
2. short circuit

3. thermal, mechanical
4. negative, positive
5. polarity
6. opening
7. off
8. positive, negative
9. source, load, conductors
10. open

Self-Test 9

1. power
2. 9
3. 750 W
4. $19.2\ \Omega$
5. 3000 W
6. 913 mA
7. 109.5 V
8. $12\ \Omega$
9. 12.5 A
10. It will double.

Self-Test 10

1. The needle will deflect down below the zero of the scale and possibly damage the meter.
2. parallax
3. parallel
4. voltage coil, current coil, power
5. series
6. the highest AC voltage range
7. If any there is any continuity between the leads, the battery will drain.
8. Zero the meter.
9. See Table 1.

Table 1: Meter readings

Switch position	Pointer 1	Pointer 2	Pointer 3
1	95 V DC	165 V DC	235 V DC
2	1.25 V AC	2.05 V AC	2.80 V AC
3	380 mA DC	660 mA DC	940 mA DC
4	750 k Ω	220 k Ω	30 k Ω

Self-Test 11

1. creating heat, controlling current and regulating voltage
2. ohms and watts
3. wire-wound, carbon composition and film resistors
4. carbon composition
5. 560 000 ohms
6. 10 percent
7. wire-wound

Self-Test 12

1. False
2. False
3. a spring action
4. False
5. two
6. voltage and current
7. to minimize arcing and burning of contacts

Self-Test 13

1. 
2. False
3. current in the fuse
4. plug fuse
5. It could easily be replaced with one of higher amp rating.
6. • Advantage is cost saving.
• Disadvantage is danger of using of heavier link.
7. 60 A

8. It is easily reseatable.
9. thermal, magnetic
10. moulded case CB
11. CB cannot be held in the closed position.
12. 15, 20, 30, 40, 50, 60, and 70 A
13. False

Self-Test 14

1. c. be drawn into a wire
2. d. ultimate strength
3.
 - copper's conductance
 - oxide resistance
4. d. copper
5. b. silver
6. It is lighter.
7. d. flexibility
8. Its diameter is reduced and it is work-hardened.
9. d. silver
10. strength
11.
 - oxidation
 - malleability
12. b. bunch stranding

Self-Test 15

1. Yes. It is manufactured from materials that are not flammable.
2. Both are thermoplastic materials and weatherproof.
3. magnetic coils
4. It is marked with XLPE or X-LINK on its surface. See Table 19, Note 10.
5.
 - a. green
 - b. white (or natural grey)
 - c. red, black, blue or yellow

Self-Test 16

1. the conductors that supply the incoming power for distribution to all other consumer branch circuits; specifically, the conductors from supply connections to the line side of the main service disconnect
2. 31 to 750
3. doorbell, thermostat and remote-control wiring circuits
4. shielded
5. buildings of wood frame or combustible material construction
6. 300 V
7. 90°C = the maximum temperature rating of the conductor
8. It is the grounding wire.
9. lead sheathing over the conductors
10. a more durable, higher voltage, PVC-jacketed, armoured cable
11. The non-metallic covering can burn, transmit fire and release a highly toxic gas.
12. smooth or corrugated seamless aluminum sheath
13. polyvinylchloride (PVC)
14. because there are no flammable materials in its construction
15. a special cable-termination kit
16. for service drops and overhead distribution on private property
17. the bare conductor (acting as the neutral), wrapped about the insulated conductors as support
18. range and dryer cables
19. It is a hard-usage cable for connection to portable equipment.
20. amperage
21. copper and aluminum

Self-Test 17

1. a. True
2. a. True
3. b. False
4. b. False
5. a. True
6. a. True
7. a. 650 mils

- b. 175 mils
8. 187.5 mils
9. 130 mils
10. square mil area = $125 \times 375 = 46\,875$ square mils
CMA = $46\,875 \div 0.7854 = 59\,680$ CM
11. 1 270 000 CM
12. CMA = $64^2 = 4096$ CM
square mil area = $4096 \times 0.7854 = 3217$ SM
13. $46\,000 \times 0.7854 = 36\,130$ square mils
width = $\frac{36\,100 \text{ square mils}}{120 \text{ mils}} = 301 \text{ mils}$
14. $40\,000 \text{ CM} \times 0.7854 = 31\,420$ square mils
15. a. 218 750 square mils
b. $218\,750 \div 0.7854 = 278\,500$ CM
16. a. 187 500 square mils
b. $187\,500 \div 0.7854 = 238\,700$ CM
17. 109 375 square mils
 $109\,375 \div 0.7854 = 139\,300$ CM
18. 500 000 square mils
 $500\,000 \div 0.7854 = 636\,600$ CM

Answers to Questions 19–22 are in Table 1.

Table 1

	Mil	CM	SqM	AWG
19.	114	16 547	12 996	7
20.	64.1	4108	3227	14
21.	61	26 047	20 457	6
22.	435×120	66 463	52 200	2

23. AWG
24. smaller
25. d. circular mils
26. 1.26
27. twice as large
28. The outer edge of the AW gauge contains numbered slots.
The smallest slot into which the wire will fit is the AWG number of the wire.

Self-Test 18

1. copper wire
2. a. Its resistance would double.
b. Its resistance would halve.
c. Its resistance would remain unchanged.
3. *Positive* means an increase in resistance with an increase in temperature.
Negative means a decrease in resistance with an increase in temperature.
4. a. $20.75\ \Omega$
b. $2.08\ \Omega$
c. $3.12\ \Omega$
5. a. 1250 feet
b. 198 feet
c. 180 feet
6. $11.55\ \Omega$
7. $19.5\ \Omega$
8. $L = 15\ 024\ \text{feet}$
 $= 2.84\ \text{miles}$
 $= 4.58\ \text{km}$
9. $R = 0.25\ \Omega$
10. $R = 19.6\ \Omega$
11. $R = 10\ \Omega$
12. $R = 16.42\ \Omega$
13. $R = 260\ \Omega$
14. temperature rise = 35°C
15. operating temperature = 789°C
16. $R = 220\ \Omega$
17. $1\ \text{ohm} \times 0.5 = 0.5\ \text{ohm}$
18. c. 16.4 ohms
resistance of aluminum = resistance of copper $\times 1.64$
(1.64 = resistance ratio of copper to aluminum)

Self-Test 19

1. type of conductor material, size (area), temperature rating of insulation, ambient temperature, method of installation (free air, raceway)

2. CEC Table 1
 - a. 60 A
 - b. 140 A
 - c. 310 A
 - d. 455 A
 - e. 230 A
3. CEC Table 2
 - a. 55 A
 - b. 95 A
 - c. 35 A
 - d. 315 A
 - e. 20 A
4. CEC Table 3
 - a. 150 A
 - b. 545 A
 - c. 35 A
 - d. 315 A
 - e. 750 A
5. CEC Table 4
 - a. 320 A (TWU is rated 60°C in CEC Table 19)
 - b. 155 A
 - c. 20 A
 - d. 45 A
 - e. 230 A
6. CEC Table 1: ampacity rating in free air 80 A
CEC Table 2: ampacity rating in raceway 55 A
Difference in rating = $80 - 55 = 25$ A
7. CEC Table 12: ampacity = 18 A
8. CEC Table 36A: No. 4 AWG NS75; two insulated conductors: triplex
9. CEC Table 2: ampacity = 20 A

Self-Test 20

1. $R = \frac{K \times L}{CMA} = \frac{104 \times 2000}{204^2} = 0.4998 \, \Omega$

$$VD = 40 \times 0.4998 = 19.99 \, V$$

2. $R = \frac{10.4 \times 500}{64^2} = 1.2695 \, \Omega$

$$VD = 3 \times 1.2695 = 3.81 \, V$$

3. $R = 0.3963 \, \Omega$
 $VD = 20 \times 0.3963 = 7.93 \, V$



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