BASIC ELECTRICITY

SECOND EDITION

A SELF-TEACHING GUIDE

CHARLES W. RYAN

Basic Electricity

SECOND EDITION

A Self-Teaching Guide

CHARLES W. RYAN

JOHN WILEY & SONS, INC.

New York • Chichester • Brisbane • Toronto • Singapore

CHAPTER ONE
What is Electricity?

The word "electricity" comes from the Greek word electron (ελεκτρου), which means "amber." Amber is a translucent yellowish mineral made of fossilized resin. The ancient Greeks used the words "electric force" in referring to the mysterious forces of attraction and repulsion exhibited by amber when it was rubbed with a cloth. They did not understand the nature of this force and could not answer the question, "What is electricity?" Today, we still cannot answer the question, although the success with which we have used electricity is obvious everywhere.

Although we don't really know what electricity is, we have made tremendous strides in harnessing and using it. Elaborate theories concerning the nature and behavior of electricity have been advanced, and they have gained wide acceptance because of their apparent truth—and because they work.

Scientists have found that electricity behaves in a consistent and predictable manner in given situations or when subjected to given conditions. Scientists, such as Faraday, Ohm, Lenz, and Kirchhoff, have described the predictable characteristics of electricity and electric current in the form of certain rules, or "laws." Thus, though electricity itself has never been clearly defined, its predictable nature and ease of use have made it one of the most common power sources in modern times.

By learning the rules, or laws, about the behavior of electricity, you can "learn" electricity without ever having determined its fundamental identity.

When you have finished this chapter, you will be able to:

- describe free electrons;
- describe conductors and insulators in terms of the movement of free electrons, giving examples of each;
- relate the action of free electrons to the phenomenon of static electricity;
- describe positive and negative charges;
- state the law of attraction and repulsion of charged bodies;
- explain Coulomb's Law of Charges; and
- describe the electric field associated with charged bodies.

Free Electrons

1. The classical approach to the study of basic electricity is to begin with the "electron theory." This encompasses the nature of matter and a fairly thorough discussion of molecules and atoms. Such an approach provides a good background for the essential point: Electric current depends on the movement of free electrons. In this book, the details of electron theory, such as atomic weights and numbers, are omitted so that we may move quickly to the points you really need to know for the study of electricity.

   All matter is made of molecules, or combinations of atoms, that are bound together to produce a given substance, such as water or salt or glass. If you could keep dividing water, for example, into smaller and smaller drops, you would eventually arrive at the smallest particle that was still water. That particle is a molecule, which is defined as the smallest bit of a substance that retains the characteristics of that substance.

   The molecule of water is known in chemical notation as H_2O. That means the molecule is actually made up of two atoms of the element hydrogen (H) and one atom of the element oxygen (O). These atoms, themselves, are not water but the separate elements of which the molecule of water is composed.

   What is the relationship between atoms and molecules? ________

   ____

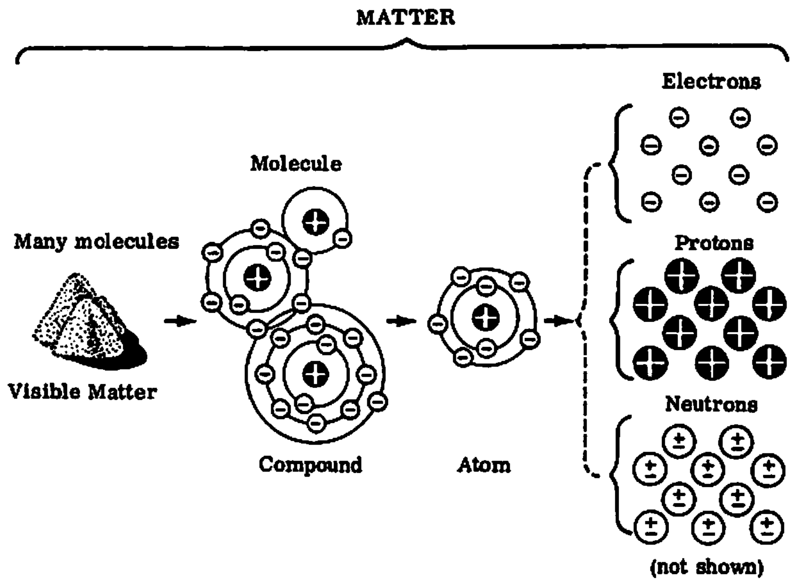
   - - - - - - - - - -

   Molecules are made up of atoms, which are bound together to produce a given substance.

2. The ancient Greeks had conceived the idea of the atom, at least in theory. In fact, atom is a Greek word that means, roughly, "not able to be divided." Today we know that the atom is composed of even smaller particles. The most important of these are the proton, the electron, and the neutron. These particles differ in weight (the proton is much heavier than the electron) and charge. The weights of the particles need not concern you, but the charge is extremely important in electricity. Perhaps you have noticed that the terminals of the battery in your car are marked with the symbols "+" and "–" or even with the abbreviations POS (positive) and NEG (negative). Many batteries used in flashlights, small electronic calculators, and other devices have similar markings. The concepts of "positiveness" and "negativeness" will become clear later. For the moment, you only need to know that the proton has a positive (+) charge, the electron has a negative (–) charge, and the neutron is neutral, which means that its positive and negative charges are in balance. Practically speaking, we say that the neutron has no charge.

   The following drawing shows the relationship of visible matter to molecules, atoms, and smaller particles: electrons, protons, and neutrons.

The drawing shows only the electrons and protons in the atoms, but every atom except hydrogen also contains neutrons.



List the three basic particles that make up the atom, and state the charge (negative, positive, or neutral) on each.

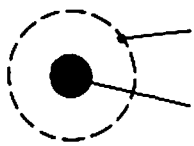
Particle	Charge
______	______
______	______
______	______

- - - - - - - - - -

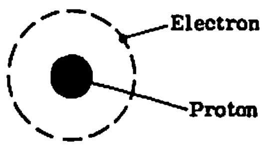
The proton is positive (+), the electron is negative (–), and the neutron is neutral.

3. As the drawing in frame 2 indicates, the atom has a nucleus (or core) that is positive because it contains only protons and neutrons. Electrons are in orbit about the nucleus, in much the same way as the earth orbits around the sun. A stable atom has the same number of electrons in orbit as it has protons in the nucleus. The nucleus always (with one exception) contains neutrons, too, but we need not consider them for our purposes because they are always neutral. Since the negative charge of the electrons is balanced by the positive charge of the protons, the atom is electrically neutral. The following drawing shows a hydrogen atom, the only one that has no neutron, so its nucleus is a single proton.

Label the electron and the proton.



- - - - - - - - - - -



4. What is the net charge on the hydrogen atom shown in frame 3? _______

Why? ____

- - - - - - - - - - -

The charge is neutral, because it has an equal number of protons and electrons (one of each).

5. Other atoms have more protons in the nucleus and more electrons in orbit. In fact, each atom has a different number of electrons and protons. In all cases, however, the electrons move around the nucleus of the atom in various orbits. Such electrons are not free: They are locked into the atom because they are attracted by the nucleus. They do not fall into the nucleus (as the earth does not fall into the sun) because their movement in orbit provides an equalizing centrifugal force.

Free electrons are produced when some force disturbs the stable relationship of electrons and protons in an atom. This force, which "knocks" electrons out of orbit, can be produced in a number of ways, such as: by moving a conductor through a magnetic field; by friction, as when a glass rod is rubbed with silk; or by chemical action, as in a battery. (The six principal methods of producing this force, called voltage, are described in Chapter 2.) The force "frees" the electrons from their atoms; these electrons are called free electrons. When an electric force is applied to a material such as copper wire, electrons in the outer orbits of the copper atoms are forced out of orbit and impelled along the wire. The electrons that have been forced out of orbit are called ______________________.

- - - - - - - - - - -

free electrons

6. The movement of free electrons along a wire is what we call electric current. It cannot exist where there are no free electrons. What are free electrons? ______________________________

- - - - - - - - - -

Electrons that have been forced out of their atomic orbits (or any similar wording that makes this point).

7. Explain in your own words the flow of electric current in a copper wire when an electric force is applied to the wire. ____________________

____

____

- - - - - - - - - -

Something like: When an electric force is applied to a copper wire, free electrons are displaced from the copper atoms and move along the wire, producing electric current.

Conductors and Insulators

8. Electric current moves easily through some materials but with greater difficulty through others. Let us see how the action of free electrons is related to current flow through these materials. Substances that permit the movement of a large number of free electrons are called conductors. Copper wire is considered a good conductor because it has many free electrons when an electric force is applied to it. Electrical energy is transferred through a conductor by means of the movement of free electrons that migrate from atom to atom inside the conductor. Each electron moves the very short distance to the neighboring atom, where it replaces one or more electrons by forcing them out of their orbits. The displaced electrons repeat the process in other nearby atoms until the movement is transmitted throughout the entire length of the conductor.

The movement of each electron takes a very small amount of time, but the electrical impulse is transmitted through the conductor at the speed of light, or 186,000 miles per second. To see how this is possible, imagine a line of billiard balls that almost, but not quite, touch. When the ball at one end is struck by the cue ball, the ball at the other end is knocked away from the line almost instantly. The force travels through the line of billiard balls much more rapidly than each individual ball moves. This is basically how the electrical impulse travels. (Keep this in mind later in the book, when events in an electrical circuit seem to occur simultaneously.)

Does electric current more closely resemble the actual movement of free electrons or the impulses transmitted as the electrons bounce against one another? ____________________

- - - - - - - - - -

the impulses

9. Silver, copper, and aluminum all have many free electrons (the electrons are said to be "loosely bound") and are thus good conductors. Copper is not as good a conductor as silver, but it is the most commonly used material for electrical wiring because it is a relatively good conductor and is much less expensive than silver. Here are six metals listed in the order of the ease with which electrons are displaced from the atoms:

    silver
    copper
    aluminum
    zinc
    brass
    iron

   If we say that silver is a better conductor than iron, what do we mean?

   ____

   - - - - - - - - - - -

   Electrons are displaced from silver atoms more easily than from iron atoms.

10. Some substances, such as rubber, glass, and dry wood, have very few free electrons; the electrons are said to be "tightly bound." Such substances are <u>poor</u> conductors and are usually called <u>insulators</u>. Circle the material that is the best <u>insulator</u> among those named:

    silver   glass   zinc   brass

   - - - - - - - - - - -

   glass

11. A good conductor, then, has many free electrons, while a good insulator has few free electrons. Dry air, glass, mica, rubber, asbestos, and bakelite are all good insulators. If we say that dry air is a better insulator than bakelite, what do we mean? ______________________

   ____

   - - - - - - - - - - -

   Dry air has fewer free electrons than bakelite.

12. Write the materials listed below in the appropriate columns on the following page as either conductors or insulators. (Don't worry about the exact order.)

    glass   silver   rubber   dry air   copper   brass   mica

Conductors	Insulators

- - - - - - - - - - -

Conductors: silver, copper, brass
Insulators: glass, rubber, dry air, mica

13. Define a good conductor. ____________________

- - - - - - - - - - -

A material that has many free electrons.

14. Define a good insulator. ____________________

- - - - - - - - - - -

A material that has few free electrons.

15. Name three materials that are good conductors. ____________________

____

- - - - - - - - - - -

These have been mentioned in this chapter: silver, copper, aluminum, zinc, brass, and iron.

16. Name three materials that are good insulators. ____________________

____

- - - - - - - - - - -

These have been mentioned in this chapter: dry air, glass, mica, rubber, asbestos, and bakelite.

Static Electricity

17. Static electricity is found in nature, so we shall examine this phenomenon before we study "man-made" electricity. One of the fundamental laws of electricity must be clearly understood to understand static electricity: Like charges repel each other and unlike charges attract each other.
A positively charged particle and a negatively charged particle will tend to move toward one another. This is true even in a single atom. What kind of particle will a proton attract, and why? Write your answer in the blank on the next page.

____

____

- - - - - - - - - - -

An electron; because the proton is positive, while the electron is negative.

18. The electrons do not actually move toward the protons in the nucleus of an atom. The force of attraction is resisted by centrifugal force. If you have ever swung a bucket of water in a circle, you have seen an example of centrifugal force. The force of gravity was not able to pull the water out of the bucket, because centrifugal force opposed gravity and kept the water in. In the same way, electrons are kept in orbit around the nucleus by centrifugal force, which resists the pull of the protons in the nucleus. Why is there a force of attraction between the protons in the nucleus and the electrons in orbit? ____________________

____

- - - - - - - - - - -

Because protons (positive) and electrons (negative) are unlike charges, and unlike charges attract each other (or similar wording).

19. Will a proton attract or repel another proton? __________ Why?

____

- - - - - - - - - - -

Repel; because all protons are positive and like charges repel each other.

20. Two particles can have <u>unlike</u> charges even if neither is positive (or if neither is negative). A neutron is neutral; that is, it is neither negative nor positive. A proton is more positive than a neutron, so the two particles have unlike charges. Do the electron and the neutron have like or unlike charges? __________ Why? ________________

____

- - - - - - - - - - -

Unlike; because the electron is more negative than the neutron.

21. Two neutrons will neither attract nor repel each other, because they are neutral; that is, they have no charge. For each pair of particles listed on the following page, state whether the particles will attract or repel each other.

(1) proton and electron ____________

(2) proton and neutron ____________

(3) electron and neutron ____________

(4) electron and electron ____________

(5) proton and proton ____________

- - - - - - - - - -

(1) attract; (2) attract; (3) attract; (4) repel; (5) repel

22. State in your own words the law of attraction and repulsion. ____________

- - - - - - - - - -

Unlike charges attract each other and like charges repel each other.

23. Let us begin our study of static electricity with an experiment you can try right now. Tear up some paper into small bits and place them on a table or other hard, nonconducting surface. Now run a comb rapidly through your hair a few times, then move the comb near the bits of paper.

What happened? ____________

- - - - - - - - - -

The bits of paper were drawn to the comb. (At least, that's what should have happened!)

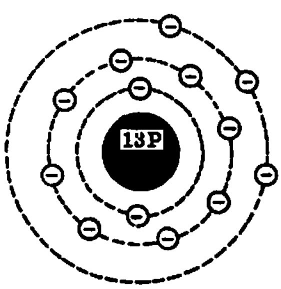
24. The experiment you have just made is a demonstration of <u>static electricity</u>. When two bodies of matter have unequal charges and are near one another, an electric force (the force of attraction or repulsion) is exerted between them. But, because they are not in contact—or are not connected by a good conductor—their charges cannot equalize. When such an electric force exists, and current cannot flow, it is called <u>static electricity</u>. "Static" means "not moving." The electric force that exists under these conditions is also called an <u>electrostatic</u> force. What two conditions are necessary for static electricity to exist? ____________

- - - - - - - - - -

Two bodies of unequal charges must be brought near one another, and current must not be able to flow between them.

25. Each atom, in its natural—or neutral—state, has the proper number of electrons in orbit about its nucleus. That is, it has the number of electrons that helps to give the element its identity. Thus, the whole body of matter composed of neutral atoms will also be electrically neutral. Matter in this neutral state is said to have no charge and it will neither attract nor repel other neutral matter in its vicinity.

The atom of each element, in the neutral state, has a different number of electrons in orbit. Hydrogen has one, helium has two, etc. A model of an aluminum atom is shown below. It has 13 electrons in orbit balanced by 13 protons (P) in the nucleus. The nucleus also contains neutrons, but they need not concern us because they are electrically neutral.



The aluminum atom shown is electrically neutral. Why? __________

____

- - - - - - - - - - -

Because it has the same number of electrons and protons.

26. But the three electrons in the outer orbit are easily displaced. If one (or more) of the electrons is knocked out of orbit, what is the charge on the atom? ________________ Why? ______________________________

____

- - - - - - - - - - -

Positive; because there are more protons (which are positive) than electrons.

27. Most substances, such as the hair, paper, and comb used in your experiment, are compounds rather than elements. That is, they are composed of atoms of various elements bound together in molecules of the substance. Their electrons are not easily displaced by an electric force. (You might have guessed that hair, paper, and combs are all relatively good insulators.) But the electrons can be displaced by friction, and this is what happened when you combed your hair vigorously in the experiment.

At the beginning of the experiment, your hair, the comb, and the paper were all electrically neutral. When you combed your hair, friction displaced electrons from your hair, and they were collected on the comb. At that point, what was the charge on the comb? ______________ Why? ______________________________

- - - - - - - - - - -

Negative; because the comb had an excess of electrons.

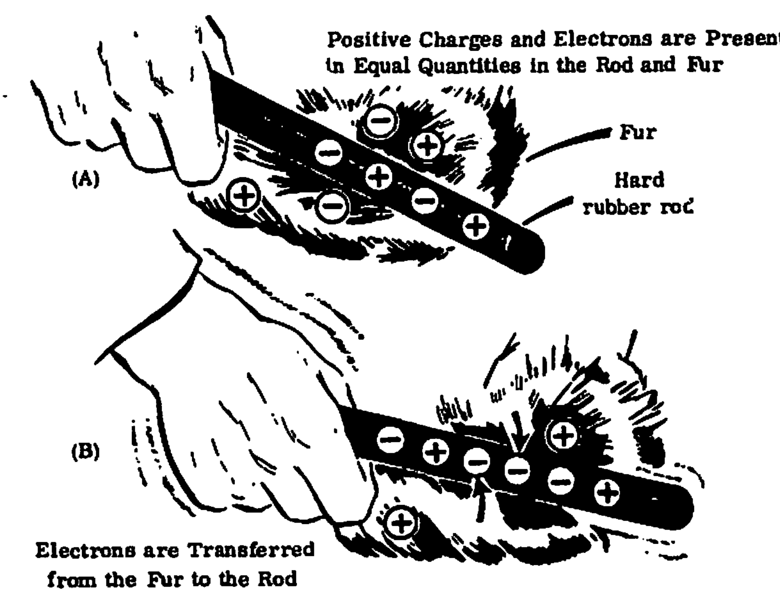
28. After the electrons were accumulated on the comb, bits of the neutral paper were attracted to the comb. Why? ______________________________

- - - - - - - - - - -

The comb and paper had unlike charges, and unlike charges attract.

29. One of the easiest ways to create a static charge is by friction. Two pieces of matter are rubbed together, and electrons are "wiped" off one and deposited on the other. The materials used can't be good conductors; if they were, an equalizing current would then flow easily in and between the conducting materials. A static charge is most easily obtained by rubbing a hard nonconducting material against a soft or fluffy nonconductor.

The drawing below illustrates how electrons are displaced from a piece of fur and deposited on a hard rubber rod.



In the case just illustrated, electrons are transferred from the fur to the rod because they are more easily displaced from the fur. When the hard rubber rod is rubbed with the fur, the rod accumulates electrons. Since both fur and rubber are poor conductors, little equalizing current can flow, and an electrostatic charge is built up. When the charge is great enough, equalizing current will flow regardless of the poor conductivity of the materials. This current may cause a crackling sound, and if it is dark, sparks can be seen.

If a body with a positive charge (too few electrons) comes into contact with a body that has a negative charge (too many electrons), an electric current will flow between the two bodies. Electrons will leave the negatively charged body and enter the positively charged body. The electric current will continue to flow until the charges of the two bodies are equal.

When a body has too many electrons, these electrons do not go into orbit around individual atoms. They are free electrons that give the material an overall negative charge.

When the electric current flows to equalize the charges on the two bodies, static electricity is said to be "discharged." The bodies do not need to touch if the difference between the charges is great enough. An example of this is the lightning that leaps between clouds or between a cloud and the earth during a thunderstorm.

Perhaps you have walked across a carpet and then have touched a bit of metal or even another person, at which time you experienced a slight shock. If so, it is because your body had acquired a negative charge, which could not be dissipated. Later, the shock resulted from the current flow when a touch allowed the charges to equalize. When the static electricity was discharged, the charges were equalized.

What is static electricity? ______________________________

____

- - - - - - - - - -

Static electricity is the force that exists between unequally charged bodies when current cannot flow between them (or equivalent wording).

30. Try to list one or two other examples of static electricity in everyday life.

____

____

- - - - - - - - - -

You can probably think of several. Clothes that cling and crackle when they are removed from an electric dryer are charged with static electricity. And if you have ever rubbed a cat's fur in the dark on a cold night, the sparks you saw were the result of static electricity.

We have seen how the behavior of charged bodies is related to static electricity. We shall examine electric fields and then continue the study of charged bodies in the next two sections.

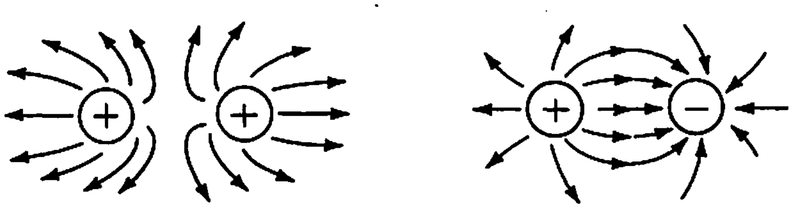
If you plan to take a break pretty soon, do it now.

Electric Fields

31. The space between and around charged bodies, in which their influence is felt, is called an electric field. (It may also be called an "electrostatic field," a "force field," or a "dielectric field.") The field always emanates from material objects and extends between bodies with unlike charges. The fields of force spread out in the space surrounding their points of origin, constantly diminishing as the distance from those points increases.

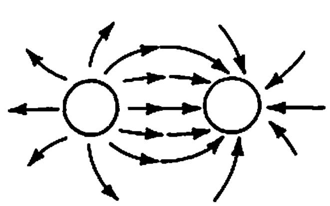
The field about a charged body is generally represented by lines called electrostatic lines of force. The lines represent the direction and strength of the field. Since a field can exist between a charged body and a neutral body, "positive" can mean "less negative," and "negative" can mean "less positive."

The drawing below represents two pairs of charged bodies. One pair has a positive (+) charge on each body (like charges), while the other pair has a positive charge on one body and a negative (–) charge on the other (unlike charges). The lines of force are indicated in each case.



This system of representing lines of force is merely a convention. Although we can measure an electric field, we do not know its exact nature.

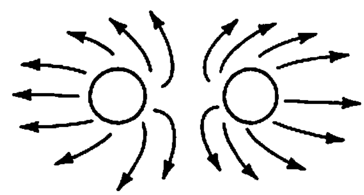
Show the charge on each body shown below by drawing the symbol for either positive or negative. (There is more than one correct answer.)



- - - - - - - - - - -

One body should be marked positive (+) and the other, negative (–), because unlike charges attract.

32. Show the charge on each body shown below as either positive or negative. (There is more than one correct answer.)



- - - - - - - - - - -

You should have labeled both bodies as positive (+) or both bodies as negative (–), because like charges repel.

33. As the electric lines of force travel out into space, does strength of the field increase or decrease? ______________________

- - - - - - - - - - -

It decreases. (If you weren't sure about this, review frame 31 before you go on.)

34. What is an electric field? ______________________

____

- - - - - - - - - - -

The space between and around charged bodies in which their influence is felt. (If you missed this, review frame 31.)

Next we shall study Coulomb's Law of Charges, which describes in more detail the force that exists between charged bodies.

Coulomb's Law of Charges

35. The Frenchman Charles A. Coulomb developed the law that governs the amount of attracting or repelling force between two electrically charged bodies in free space. This law must be understood before we study electric current, which is introduced in Chapter Two. Coulomb's formulation, known as Coulomb's Law of Charges, states:

> Charged bodies attract or repel each other with a force that is directly proportional to the product of their charges and that is inversely proportional to the square of the distance between them.

This law seems complicated, but it can be broken down into two factors:

1. The attracting or repelling force depends on the strength of the charges on the two bodies.
2. It also depends on the distance between the bodies.

Coulomb's Law of Charges takes into account what aspects of any two charged bodies? ______________________________

- - - - - - - - - -

The strength of the charges and the distance between the bodies.

36. Coulomb's Law says that the force is directly proportional to the product of the charges on the two bodies. That is, the charge of the first body is multiplied by the charge of the second body. Without worrying about the exact amount of the charges, let's give them number values. The first body has a charge of 2 and the second has a charge of 3. With these numbers assigned, the force is directly proportional to a product of

____

- - - - - - - - - -

2 x 3 = 6. (If your answer was "5," you were thinking of the sum of the charges, not the product.)

37. If the charges are increased so that their product is 12 instead of 6 (while the distance between the bodies remains the same), the force will be

______________ as much.
(half/twice)

- - - - - - - - - -

twice

38. The force is directly proportional to the product of the charges, but it is inversely proportional to the square of the distance. "Inverse" is the opposite of "direct." In mathematics, an inverse relationship is shown as a reciprocal. For example, 1/4 is the reciprocal of 4, 1/5 is the reciprocal of 5, etc. The inverse of 2 is 1/2. What is the inverse of 4?

____

- - - - - - - - - -

1/4

39. The "square" of the distance merely means the distance multiplied by itself. If the distance between two objects is 3 meters, for example, the square of the distance is 9 meters. If the distance between two objects

is 4 centimeters, what is the square of the distance?

____

\- - - - - - - - - - -

16 centimeters

40. This inverse/square formula is common to all known electromagnetic phenomena. If the distance from a light source, for example, is doubled, the illumination is quartered. Assume that the distance between two charged bodies is 1 centimeter. If the charge on each body remains the same, but the distance is increased to 2 centimeters, the attracting or repelling force is (1/2, 1/4, 1/8) ________ what it was before.

\- - - - - - - - - - -

1/4

41. The force between charged bodies can be calculated using Coulomb's Law. However, you are not required to learn the mathematics for doing so in this book. For now, you need only a general understanding of the relationship between charged bodies.

    If the total charge on two charged bodies is increased, and the distance between them remains the same, is the force increased or decreased?

____

\- - - - - - - - - - -

It is increased.

42. If the total charge remains the same and the distance between the bodies is increased, is the force increased or decreased? ______________

\- - - - - - - - - - -

It is decreased.

In this chapter you have learned the nature of free electrons, on which electric current depends. You have learned why some materials are good conductors and some are not. You have learned the nature of static electricity and how to produce it. You have also learned how charged bodies attract or repel each other. Finally, you have learned how electric fields behave and have been introduced to Coulomb's Law of Charges.

When you feel you understand all the material in this chapter, turn to the Self-Test.

Self-Test

The following questions will test your understanding of Chapter One. Write your answers on a separate sheet of paper and check them with the answers provided following the test.

1. Name the particle in an atom that has each of the following charges: (a) positive; (b) negative; (c) neutral.
2. What are free electrons?
3. Explain in your own words the flow of electric current in a copper wire when an electric force is applied to the wire.
4. Define a good conductor.
5. Define a good insulator.
6. Give three examples of good conductors.
7. Give three examples of good insulators.
8. State the law of attraction and repulsion of charged bodies.
9. What is static electricity?
10. What is an electric field?
11. According to Coulomb's Law of Charges, what two factors affect the force between two charged bodies?
12. State whether the force between two charged bodies will increase or decrease under each of the following conditions.
    (a) The charge is increased while the distance remains the same.
    (b) The distance is increased while the charge remains the same.

Answers

If your answers to the test questions do not agree with the ones given below, review the frames indicated in parentheses after each answer before you go on to the next chapter.

1. (a) proton, (b) electron, (c) neutron (2)
2. Electrons that have been forced out of orbit about their original atoms. (6)
3. When an electric force is applied to a copper wire, free electrons are displaced from the copper atoms and move along the wire, producing electric current. (7)
4. A material that has many free electrons. (13)
5. A material that has few free electrons. (14)
6. Any three: silver, copper, aluminum, zinc, brass, iron. (15)

7. Any three: dry air, glass, mica, rubber, asbestos, bakelite. (16)

8. Unlike charges attract each other and like charges repel each other. (22)

9. The force that exists between unequally charged bodies when current cannot flow between them. (29)

10. The space between and around charged bodies in which their influence is felt. (34)

11. The strength of the charges and the distance between the bodies. (35)

12. (a) increase, (b) decrease (41, 42)

CHAPTER TWO
Understanding Voltage, Current, and Resistance

Throughout most of this book, you will be working with electric circuits. Later in the book, you will learn in detail just what an electric circuit is. For now, you only need to know that it is a complete path for current flow from a battery, or some other source of voltage, through one or more conductors back to the voltage source.

While you will have to understand various circuit factors from time to time, you will almost constantly manipulate values assigned to the three basic circuit factors: voltage, current, and resistance. These three variables are interrelated, so first you must know what they are and how each affects the total electric circuit.

You will also have to know something about magnetism, since alternating-current theory is based on this phenomenon. Magnetism will be discussed in Chapter Six.

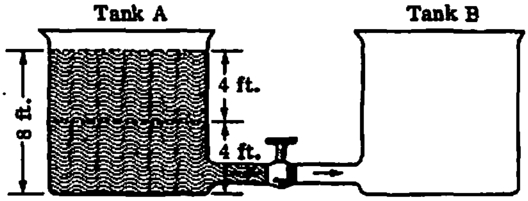
When you have finished this chapter, you will be able to:

- relate electromotive force (voltage) to the flow of electric current;
- describe the difference between direct current and alternating current;
- describe the function of resistance in limiting current flow and the factors that affect resistance;
- write and use the symbols representing voltage, current, and resistance;
- describe some general methods of producing voltage; and,
- distinguish between wet-cell and dry-cell batteries and describe their components.

Difference in Potential

1. Just as water pressure causes water to flow in pipes, an electrical "pressure," called a difference in potential, causes current to flow in a conductor. Since a difference in potential causes current flow, you need to understand what this is before you can grasp the concept of current

flow. In the drawing below, part of the water in Tank A will flow into Tank B when the valve is opened. Draw a line across Tanks A and B to indicate where you think the water level will be after the water has stopped flowing.



- - - - - - - - - - -

Your line should be across the approximate middle of both tanks. The water will flow from Tank A to Tank B until the water level is equal in the two tanks.

2. Why do you think part of the water flowed into Tank B when the valve was opened? ______________________________

- - - - - - - - - - -

The water pressure in Tank A was greater.

3. The "water tank" analogy is useful in understanding one of the basic concepts in electricity: difference in potential. The force that causes free electrons to move in a conductor as electric current is known as the difference in potential. It is also called electromotive force (emf); but you are probably familiar with the most common term, voltage. All three of these terms are interchangeable. In dealing with electricity we naturally need some units of measurement. The unit of measurement of voltage is very common and similar to the word "voltage." What do you think that unit of measurement is? ______________

- - - - - - - - - - -

the volt

4. When a difference of potential exists between two charged bodies that are connected by a conductor, electrons will flow along the conductor. This flow is from the negatively charged body to the positively charged body. Why is this so? ______________________________

____

- - - - - - - - - - -

Because electrons are negative and like charges repel, while unlike charges attract.

5. The water stops flowing between two tanks when the pressure on the two tanks is equal. The force with which the water flows, however, is not constant. When do you think that force is greatest? ______________

____

- - - - - - - - - - -

You're right if you said: when the pressure differential (difference in pressure) is greatest.

6. The force with which the water flows between the tanks is directly proportional to the pressure differential. Similarly, current flow through an electric circuit is directly proportional to the difference in potential (or voltage) across the circuit. What happens to current flow when the difference in potential is increased? ______________________

- - - - - - - - - - -

Current flow increases.

7. If voltage is increased, current is ______________. If voltage is decreased, current is ______________.

- - - - - - - - - - -

increased; decreased

8. What is the effect on current flow if the voltage is doubled? ________

____

- - - - - - - - - - -

Current flow doubles.

9. "Voltage" is also called ______________________________ or ______________________________.

- - - - - - - - - - -

electromotive force (emf) or difference in potential

10. The abbreviation for "electromotive force" is ______________.

- - - - - - - - - - -

emf

11. Tell in your own words what is meant by the statement, "Current is directly proportional to voltage." ______________________________

____

- - - - - - - - - -

Something like: "When voltage is increased or decreased, current is increased or decreased accordingly."

Electric Current

12. The drift or flow of electrons through a conductor is called electric current or electron flow. Some conventional textbooks make a distinction between current flow and electron flow. Everyone concedes that electron flow is from a negative to a positive terminal, since electrons are negative, and like charges repel. However, some authorities think of current flow as from positive to negative. Since the concepts of "positive" and "negative" are constantly encountered in the theory of electricity, it is important to avoid any confusion about the direction of current flow. In this book, we will make no distinction between current flow and electron flow. The terms current flow and electron flow are interchangeable; therefore, the direction of current flow is from _________________ to _________________.

- - - - - - - - - -

negative to positive

13. Electric current is generally classified into two general types: direct current (dc) and alternating current (ac). Direct current does not change its direction of flow. Alternating current periodically reverses direction. These two types of current will be discussed thoroughly later in the book. The common battery is a source of direct current. Does the current flow from a battery change direction? _________

- - - - - - - - - -

no

14. The current that lights your house changes direction many times per second. What type of current is it? ______________________________

- - - - - - - - - -

alternating current

15. What is direct current? ______________________________________

____

\- - - - - - - - - -

Current that does not change its direction of flow.

16. What is alternating current? __________________________________

____

\- - - - - - - - - -

Current that periodically changes its direction of flow.

17. The greater the voltage, the greater the current flow. Current is measured in amperes (often called "amps" for short). One ampere may be defined as the flow of 6.28 x 10^{18} electrons per second past a fixed point in a conductor (but you don't have to know that). Since both quantity and time are involved, the ampere indicates a rate of current flow. Your house fuses (or circuit breakers) are rated in amperes; that is, the rate of current flow that will blow the fuse or trip the circuit breaker. A fuse will blow when too many ________________ of current flow in its circuit.

\- - - - - - - - - -

amperes

18. The ampere is a measurement of the rate of current flow. The unit that measures the quantity of electrons is the coulomb, which is defined as one ampere of current flowing for one second. If we want to measure the quantity of electrons, rather than the rate of current flow, what unit would we use? ________________

\- - - - - - - - - -

coulomb

19. Thus, electromotive force (the "pressure" that causes electrons to move) is measured in ______________. The rate of flow of electric current is measured in ______________. The quantity of electrons is measured in ______________.

\- - - - - - - - - -

volts; amperes; coulombs

20. Each of these units has a standard symbol that is used in circuit drawings and equations. The symbol for voltage is the first letter of the phrase, "electromotive force," or E. The symbol for the quantity of electricity, which is measured in coulombs, is Q. The rate of current flow, which is measured in amperes and is very important in the study of electricity, is represented by the symbol I. Write the symbols corresponding to the units of measurement listed below.

ampere ________

coulomb ________

volt ________

- - - - - - - - - -

ampere, I; coulomb, Q; volt, E

21. For each of the following symbols, name the unit represented and tell what the unit measures.

Q ________________________________

E ________________________________

I ________________________________

- - - - - - - - - -

Q, coulomb, measures the quantity of electricity. E, volt, measures the electromotive force. I, ampere, measures the rate of current flow.

Resistance

22. In Chapter One you learned about good conductors and poor conductors (insulators). You learned that free electrons, or electric current, could move easily through a good conductor, such as copper, but that an insulator, such as glass, was an obstacle to current flow. Every material—even copper or silver—offers some resistance, or opposition, to the flow of electric current through it. If the material offers high resistance to current flow, it is termed an insulator. If its resistance to current flow is low, it is called a conductor. The amount of current that flows in a given circuit depends on two factors: voltage and resistance (represented by the symbol R). Thus the amount of current that flows in a circuit can be changed by changing either ______________ or ______________.

- - - - - - - - - -

voltage (E); resistance (R)

23. The unit of resistance is the ohm, named for the man who developed Ohm's Law, which you will study in Chapter Three. Resistance, as the word implies, is the ability of a material to impede the flow of electrons. (If you later study advanced electricity, you will encounter another concept of electricity, conductance, which is the opposite of resistance, but you do not need this concept to understand the material in this book.)

Current is measured in amperes, and voltage is measured in volts.

Resistance is measured in ________________.

- - - - - - - - - -

ohms

24. The abbreviation for "volts" is "v." "Amperes" is abbreviated "a." But the small letter "o" looks too much like "a," and "ohm" would be awkward and tiresome to indicate values of resistance. Thus the Greek letter omega (Ω) is used as an abbreviation for "ohms." "Ten amperes" is abbreviated "10 a." Write the abbreviation for "10 ohms" below.

____

- - - - - - - - - -

10 Ω

25. Give the abbreviations for the following units of measurement.

amperes __________

volts __________

ohms __________

- - - - - - - - - -

amperes, a.; volts, v.; ohms, Ω

26. The wires that carry current in an electric circuit are usually made of copper, because it is both a good conductor and relatively inexpensive. But the size of the wires is a factor, too. Just as water flows more easily (at a given pressure) in a large pipe than in a small one, electric current flows more easily (at a given voltage) in a large (greater diameter) wire than in a small one. In an electric circuit, at a given voltage, the larger the diameter of the wires, the (higher/lower) ________________ will be the current flow.

- - - - - - - - - -

higher

27. If voltage is held constant, current flow depends on the resistance of the wires (and other devices) in the circuit. A larger diameter wire offers less resistance to current flow than a smaller diameter wire, but one other factor affects the total resistance to current flow: the <u>length</u> of the wires. Since the material of the wires offers resistance to current flow, increasing the amount of material (for a given diameter) increases total resistance. Increasing the length of the wires in an electric circuit has what effect on resistance? ______________________________

______________________ This in turn has what effect on the amount of current flowing in the circuit? ____________________

____

- - - - - - - - - - -

It increases resistance; it decreases the amount of current flow.

28. It would not be practical to change the rate of current flow by changing the size or length of the wires. Electrical circuits require varying amounts of current flow for different uses. For that reason, parts are manufactured that present precise amounts of opposition or resistance to current flow. These devices are called, not very surprisingly, <u>resistors</u>. The amount of resistance is measured in <u>ohms</u>. (Although you don't need to know it at this point, one ohm is the resistance in a circuit that permits a steady current of one ampere—one coulomb per second—to flow when a steady emf of one volt is applied to the circuit.) If you want to increase the current flow in a circuit, one way is to take out a resistor and replace it with one rated at (more/fewer) ______________ ohms.

- - - - - - - - - - -

fewer

29. Without changing the wiring or values of resistors, how could you increase current flow? ______________________________________

- - - - - - - - - - -

By increasing the voltage applied to the circuit.

30. How does increasing the diameter of the wires affect resistance?

____

- - - - - - - - - - -

Resistance is decreased.

31. Increasing the length of the wires in a circuit has what effect on resistance? ______________________

- - - - - - - - - -

Resistance is increased.

32. Increasing the voltage applied to a circuit has what effect on current flow? ______________________

- - - - - - - - - -

It increases current flow.

33. Without changing the wiring, resistors, or other devices in a circuit, how could you decrease current flow? ______________________

- - - - - - - - - -

Decrease the voltage.

34. Later you will use the symbols E, I, and R in equations to solve problems involving electric circuits, so it is important that you remember them.

The symbol for voltage is __________; for current, __________; and for resistance, __________.

- - - - - - - - - -

voltage, E; current, I; resistance, R

Primary Methods of Producing a Voltage

35. There are many ways to produce electromotive force, or voltage. On the following page, match the six most common methods in the first column with their appropriate descriptions in the second column.

________	1. FRICTION	(a)	Voltage produced by heating the junction where two unlike metals are joined.
________	2. PRESSURE	(b)	Voltage produced in a conductor that is moved in a magnetic field.
________	3. HEAT	(c)	Voltage produced by squeezing certain crystals (piezoelectricity).
________	4. LIGHT	(d)	Voltage produced by the use of certain photosensitive substances.
________	5. CHEMISTRY	(e)	Voltage produced in a battery cell.
________	6. MAGNETISM	(f)	Voltage produced by rubbing two materials together.

- - - - - - - - - - -

1. (f); 2. (c); 3. (a); 4. (d); 5. (e); 6. (b)

36. In understanding the fundamentals of electricity, you will be most concerned with chemistry and magnetism as means to produce voltage. Friction has little practical application, although we discussed it earlier in studying static electricity. Heat, light, and pressure do have useful applications, but we do not need to consider them in the early stages of study. Chemistry and magnetism, on the other hand, are the principal sources of voltage. Anyone who drives a car is familiar with one of these voltage sources, because if it is dead or missing, the car can't be started. This voltage source, which uses chemistry as its basis, is the

________________.

- - - - - - - - - - -

battery

37. But the battery alone cannot keep the automobile running. A generator, or alternator, supplies the voltage necessary for running the engine and keeping the battery charged. This device operates by moving a conductor in a magnetic field. Thus, an understanding of both chemical action and magnetism is necessary to understand practical electricity. A generator produces alternating current and uses the principles of magnetism. A battery employs which of the six methods of producing voltage?

____

- - - - - - - - - - -

chemistry

Batteries

38. Batteries are widely used as sources of direct-current electrical energy in automobiles, boats, aircraft, portable electric and electronic equipment, and lighting equipment. A battery consists of a number of cells assembled in a common container and connected together to function as a source of electrical power. The ordinary flashlight battery is not actually a battery but a cell, according to this definition, because two or more "batteries" (which are actually cells) operate together to provide the power. Which parts of a flashlight make up the true battery? ____________

____

- - - - - - - - - -

The cells and the barrel of the flashlight, which contains the cells (or some similar wording). The bulb, lens, and switch are not part of the battery.

39. The cell is the device that transforms chemical energy into electrical energy. It consists of a positive electrode (carbon), a negative electrode (zinc), a chemical solution, and a glass container. The chemical solution is the electrolyte.

Aside from the container in which they are assembled, the basic parts of a simple cell are: two ____________, and a chemical solution called the ____________.

- - - - - - - - - -

electrodes; electrolyte

40. The basic device that transforms chemical energy into electrical energy is the ____________.

- - - - - - - - - -

cell

41. A ____________ consists of two or more cells assembled in a common container to produce electricity.

- - - - - - - - - -

battery (Note: You could have a battery with only one cell, but this is not usually the case.)

42. What is the relationship between a cell and a battery? ______________

____

- - - - - - - - - - -

The battery includes the cells and the container.

43. The cells of a battery are like "mini-batteries." The battery has internal electrical connections between the cells, and then the battery provides power to some external circuit. Each cell provides part of the power to the entire circuit. The electric current that flows in a circuit "powered" by a cell consists of free electrons that leave the (negative/positive) ______________________ electrode and return to the cell through the (negative/positive) ______________________ electrode. (Hint: Like charges repel.)

- - - - - - - - - - -

negative; positive (Note: Electrons are negative, so they are repelled by the negative electrode and attracted by the positive electrode.)

44. The simple cell consists of two electrodes suspended in a chemical solution called an electrolyte. (The electrodes are usually strips, rods, or sheets of two different materials. The most common materials are carbon and zinc, but you don't need to know that for this book.) The battery works because of the interaction between the chemical solution and the two dissimilar materials. Thus, you might say that chemical energy results from the interaction of the two different materials, called ____________, and the chemical solution, called the ____________________.

- - - - - - - - - - -

electrodes; electrolyte

45. Batteries are classified as either wet-cell or dry-cell batteries. The difference lies in the form of the electrolyte. The wet cell has a liquid electrolyte, but the dry cell is not completely dry; its electrolyte is actually a damp paste. (If it were completely dry, there would be almost no chemical action.) A common example of the wet-cell battery is the storage battery in an automobile. An example of the dry-cell battery is the common flashlight. The major difference between a wet-cell battery and a dry-cell battery is in the form of the ______________________.

- - - - - - - - - - -

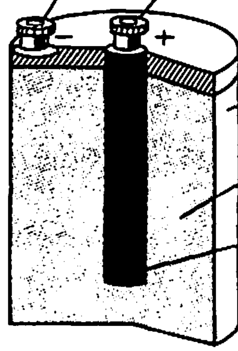
electrolyte

46. What general type of battery has cells whose electrodes are suspended in a liquid electrolyte? ________________ Which type has an electrolyte that is a wet paste? ________________

\- - - - - - - - - -

The wet-cell battery; the dry-cell battery.

47. For most applications, a dry cell is more convenient as the basic unit of a battery. Shown here is a cutaway view of a typical dry cell.



Which part of the cell is the negative electrode? ________________

Which part is the positive electrode? ________________

Which electrode is buried in the electrolytic paste? ________________

\- - - - - - - - - -

The negative electrode is the zinc container; the positive electrode is the carbon rod, which is buried in the electrolytic paste.

You are now able to relate electromotive force (difference in potential) to the flow of electric current and to describe how resistance limits current flow. You have become familiar with the symbols representing voltage, current, and resistance. You have learned some general methods of producing voltage as well as the types and composition of one such method: batteries. Now complete the Self-Test.

Self-Test

The following questions will test your understanding of Chapter Two. Write your answers on a separate sheet of paper and check them with the answers provided following the test.

1. One battery terminal is negative and the other is positive. What force of "pressure" causes current to flow in the circuit connecting the terminals?
2. Why is current flow in a battery-powered circuit from the negative terminal to the positive terminal?
3. What is the effect on the rate of current flow if the voltage is reduced by 50 percent?
4. What is the difference between direct current and alternating current?
5. Give the unit of measurement and symbol for each of the following: (a) difference in potential; (b) rate of current flow; (c) quantity of electricity; (d) resistance.
6. Give the abbreviation for each of the following units of measurement: (a) ampere; (b) volt; (c) ohm.
7. The rate of current flow in a circuit can be changed by changing what other two variables?
8. What three factors affect the resistance in a circuit?
9. Give two ways of increasing the resistance of the circuit wiring.
10. What are the two most widely used methods of producing a voltage?
11. What method of producing a voltage is used in batteries?
12. What is the relationship between a cell and a battery?
13. Current flows away from what electrode of a cell?
14. What are the two basic components that cause a cell to produce electricity?
15. What is the major difference between a wet cell and a dry cell?
16. What is the form of the electrolyte of a dry cell?

Answers

If your answers to the test questions to not agree with the ones given below, review the frames indicated in parentheses after each answer before you go on to the next chapter.

1. Difference in potential. (1–4)
2. Like charges repel, so the negative terminal repels electrons, which are negative. In addition, the positive terminal attracts the electrons. (4)
3. The rate of current flow is reduced by 50 percent. (6–8)

4. Direct current flow does not change direction, while alternating current periodically changes direction. (13–16)

5. (a) volt, E; (b) ampere, I; (c) coulomb, Q; (d) ohm, R (17–23)

6. (a) a.; (b) v.; (c) Ω (24–25)

7. Voltage and resistance (22)

8. The values of the resistors, the length of the conductors, and the diameters of the conductors. (26–28)

9. Make the wires longer or decrease their diameter. (30–31)

10. chemistry; magnetism (36)

11. chemistry (37)

12. The battery includes the cells and the container. (42)

13. negative (43)

14. The electrodes and the electrolyte. (44)

15. The form of the electrolyte. (45)

16. A moist paste. (46)

CHAPTER THREE

The Simple Electric Circuit

In Chapters One and Two you were introduced to some of the basic concepts of electricity. Now you will use those fundamental ideas to begin to understand the electric circuit.

You will need to know some algebra to work through this chapter and many of those that follow. If you need to learn how to solve simple equations (or if you would like a review), turn to Appendix I. The material presented there will teach you all you need to know about the math required in this book.

When you have finished this chapter you will be able to:

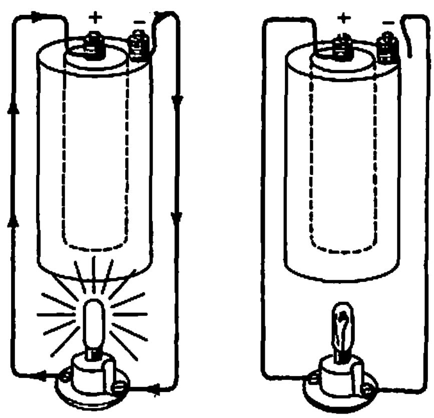
- draw schematic diagrams of simple electric circuits, using standard schematic symbols;
- solve simple equations, derived from Ohm's Law, to find voltage, current, and resistance;
- relate power consumption to voltage, current, and resistance, and solve power equations;
- solve problems about the power capacity of electrical devices; and
- relate power to energy and solve energy equations.

The Electric Circuit

Refer to Figure 3-1 on the following page for frames 1 through 7.

1. An electric circuit includes an energy source, some kind of load to dissipate the energy, and a conductor to provide a pathway for current flow. The energy source could be a battery, as in Figure 3-1, or some other means of producing a voltage. The load that dissipates the energy could be a lamp, as in Figure 3-1, a resistor, or some other device that does useful work, such as an electric toaster, a power drill, or a soldering iron. (Of course, a circuit might include a great many separate devices, or loads.) The conductor, which is usually wire, connects all the loads in the circuit to the voltage source to provide a complete pathway for current flow. No electrical device dissipates energy unless current flows through it. Since wires are not perfect conductors, they heat up (dissipate energy), so they are actually part of the load. For simplicity, how-

ever, we usually think of the connecting wiring as having no resistance, since it would be tedious to assign a very low resistance value to the wires every time we wanted to solve a problem.



(A) Closed Circuit (B) Open Circuit

Figure 3-1. (A) Simple electric circuit (closed); (B) Simple electric circuit (open).

You can check the circuit in Figure 3-1, View A, to see whether there is a complete pathway for current flow. Start at any point, and go around the circuit only once until you return to your starting point. There is no problem until you try to get from one terminal of the battery to the other. There is current flow inside the battery, but here we have a special case, because we said (in Chapter One) that current flows from negative to positive. This is true outside the battery, in what we call the external circuit, because electrons are negative. Since the negative terminal of the battery repels electrons, the current flow is away from the negative terminal and toward the positive terminal (which attracts electrons). The current flow inside the battery (the internal circuit) results from chemical action, not from the laws of attraction and repulsion, and is from the positive terminal to the negative terminal. This completes the circuit. Once you understand this special case of current flow inside the battery, you need not consider it again. Any consideration of current flow in this book is concerned with current flow in the external circuit.

Figure 3-1 shows a very simple electric circuit that includes only a battery, a light bulb, and the connecting wires. Look at the two drawings and note all the differences you see between drawing (A) and drawing (B).

- - - - - - - - - -

(1) The light bulb is lit in (A) but not in (B); (2) arrows are shown along the wire in (A) but not in (B); (3) the wire is connected to the negative (−) terminal in (A) and disconnected in (B).

2. The arrows following the wire, and the "rays" indicating that the bulb is lit, are the artist's way of showing that there is a completed electric circuit in (A) and not in (B). If there is a complete pathway for the flow of electric current, a closed circuit exists. If the pathway is interrupted by a break in the conductor (such as a disconnected wire), the result is an open circuit. Which is the closed circuit, (A) or (B)? ________

- - - - - - - - - - -

(A)

3. Which is the open circuit? ________ Why? ____________________

____.

- - - - - - - - - - -

(B); Because a wire is disconnected from the negative terminal.

4. Can you think of any other ways (besides cutting the wire) to cause an open circuit in Figure 3-1? ________________________________

____

- - - - - - - - - - -

(1) Disconnect the wire from the positive (+) terminal; (2) and (3), disconnect a wire from either side of the bulb socket; (4) unscrew the bulb.

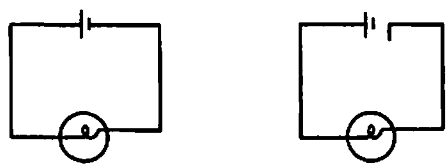
5. The arrows indicate that current flow outside the battery is from negative to positive, but you should know that anyway if you remember the law of attraction and repulsion of charged bodies (Chapter One). Why is the current flow away from the negative terminal? ____________________

____

- - - - - - - - - - -

Because electrons, which are negative, are repelled by the negative terminal and attracted by the positive terminal.

6. Each circuit shown in Figure 3-1 can be represented by a schematic diagram. A schematic diagram (usually shortened to "schematic") is a simplified drawing that represents the electrical, not the physical, situation in a circuit. Circuit elements are indicated by very simple drawings, called schematic symbols, that are standardized throughout the world, with minor variations. The following illustrations are the equivalent schematics for the closed-circuit and open-circuit configurations shown in Figure 3-1.



(A) Closed Circuit (B) Open Circuit

Now, since there are no arrows to show the direction of current flow, there is only one difference between circuit (A) and circuit (B). What is it? ________________________________

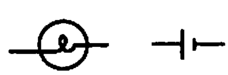
\- - - - - - - - - -

There is an open space at the top of circuit (B).

7. The drawings in Frame 6 are schematic diagrams representing the <u>electrical</u> situation in a circuit, using standardized symbols. (Conductors are simply lines.) The two schematics in Frame 6 show the symbols in the same positions as the circuit elements they represent in Figure 3-1, but this need not be so. A schematic turned on its side or upside down, or with varying line lengths for the conductors, would still be electrically the same. Compare the schematics with the drawings in Figure 3-1, then draw the symbols for a light bulb (lamp) and a battery in the space below.

light bulb battery

\- - - - - - - - - -

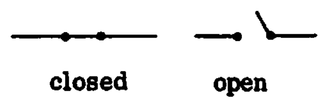


light bulb; battery

8. By convention, the shorter line in the symbol for a battery represents the <u>negative</u> terminal. It is important to remember this, because it is sometimes necessary to note the direction of current flow, which is from negative to positive, when you examine a schematic. The battery symbol shown in frame 7 has a single cell, so only one short and one long line are used. The number of lines used to represent a battery vary (and they are not necessarily equivalent to the number of cells), but they are always in pairs, with long and short lines alternating. In the circuit shown in frame 6, the current would flow in a <u>clockwise</u> direction; that is, in the direction that a clock's hands move. If the long and short lines of the battery symbol in frame 6 were reversed, the current would flow <u>counterclockwise</u>; that is, in the opposite direction of a clock's hands.

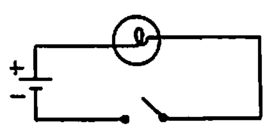
We opened the circuit in Figure 3-1 and in its corresponding schematic (frame 6) by disconnecting a wire from a terminal. Naturally, a <u>switch</u>

is used for this purpose in most circuits. Here is the schematic symbol for a switch; it may be placed anywhere in the circuit that is convenient.



Draw a schematic for an open circuit that includes a battery, a lamp, and a switch. Connect the battery so the current would flow counterclockwise, and label the battery terminals (+) and (–). Use a separate sheet of paper.

- - - - - - - - - -



Here is one possibility. The negative side of the battery is the shorter line. Your battery can have any number of pairs of lines. The other schematic symbols may be shown in any order.

Now that you are familiar with an electric circuit and its equivalent schematic diagram (other symbols will be introduced as you need them), you are ready to examine the relationships of current, voltage, and resistance. The relationships are expressed in Ohm's Law, which is the foundation on which electrical theory is based.

Ohm's Law

9. A three-cell flashlight casts a brighter beam than a two-cell flashlight using the same size batteries. Flashlights come in different sizes, from the little "penlight" on up. Someone had to decide how much voltage a cell should produce and what kind of bulb should be used, among other things. Flashlight batteries also power toys, clocks, and other devices, so circuits have to be designed to produce the correct amount of current. How does one decide what the relationships of current, voltage, and resistance should be in a circuit? If the voltage source is constant, how much voltage is required to power a device such as a radio or a washing machine? This kind of question is basic in electrical design. To answer such questions, we start with Ohm's Law.

Georg Simon Ohm, a 19th century philosopher, formulated the relationships among voltage, current, and resistance. Ohm's Law states that:

> The intensity of the current in amperes in any electric circuit is equal to the difference in potential in volts across the circuit divided by the resistance in ohms of the circuit.

You don't have to memorize the law in words, but you do have to memorize the equation that represents it:

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

Remember that I represents current expressed in amperes, E represents the difference in potential in volts, and R represents resistance in ohms. What is the effect on current if resistance is increased?

___

- - - - - - - - - -

Current is decreased.

10. What is another way to decrease current? ___

___

- - - - - - - - - -

Decrease the difference in potential (voltage).

11. Most of the resistance (sometimes called the load) in a circuit is in the form of components that do specific work, such as a bulb, and certain components, called resistors, whose purpose is to limit current flow. As you have learned, the conductors (wires) themselves have resistance that varies with the size and length of the wire, but it is not practical to limit current flow in this manner. The wire resistance becomes important in advanced electricity, but in this book, you need not consider it. Problems are simplified by ignoring the resistance of the wires. There are no resistors in the simple flashlight, so what component presents most of the resistance? ___

- - - - - - - - - -

the bulb

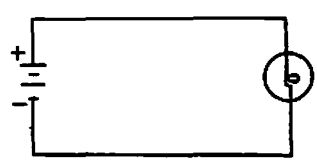


Figure 3-2. Simple electric circuit with a lamp as the load.

Refer to Figure 3-2 for frames 12 through 25.

12. Assume throughout this book that the wiring has <u>no resistance</u>. To use Ohm's Law to solve for current, voltage, or resistance, you have to know two of the values and solve for the third. To find the current flowing in the circuit shown in Figure 3-2, you need to know the values for ___ and ___.

- - - - - - - - - -

voltage and resistance

13. Write the equation for finding the current (I) when the voltage (E) and resistance (R) are known. ______________________

\- - - - - - - - - -

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

14. The lamp in Figure 3-2 is actually a resistor. The resistance of the lamp is 3Ω and the battery produces 6 v. How much current is flowing in the circuit? ______________________

\- - - - - - - - - -

2 amperes (2 a.)

Here is the solution:

$$I = \frac{E}{R} = \frac{6\text{ v.}}{3\ \Omega} = 2\text{ a.}$$

15. The voltage source (battery) produces 10 v. and the resistance of the lamp is 4Ω. How much current is flowing in the circuit? ______________

\- - - - - - - - - -

2.5 a. (10 ÷ 4 = 2.5).

16. E = 12 v.; R = 4Ω.

I = __________

\- - - - - - - - - -

3 a. (Note: Unless otherwise stated, voltage is assumed to be in volts, resistance in ohms, and current in amperes.)

17. E = 1.5 v.; R = 2Ω.

I = __________

\- - - - - - - - - -

0.75 a.

18. By now you know that $I = \frac{E}{R}$. If you want to solve for E in terms of I and R, you have to manipulate the equation to isolate E. Do so on a separate sheet of paper.

- - - - - - - - - - -

E = IR   Solution: $I = \frac{E}{R}$

Cross multiply.

E = IR

(Note: If you had trouble with this, you need to review Appendix A.)

19. Refer again to Figure 3-2. The current in the circuit is 3 a. and the resistance of the lamp is 2Ω. How much voltage is produced by the battery?

____

- - - - - - - - - - -

6 v.   (E = IR = 3 a. x 2 Ω = 6 v.)

20. The resistance of the lamp is 1 Ω and the current is 3.73 a. What is the voltage? __________

- - - - - - - - - - -

3.73 v.

21. I = 4 a.; R = 1.5Ω.

E = __________.

- - - - - - - - - - -

E = IR = 4 a. x 1.5Ω = 6 v.

22. R = 2Ω; I = 0.5 a.

E = __________.

- - - - - - - - - - -

1 v.

23. E = IR. To solve for R, you must manipulate the equation to isolate R. Do so on a separate sheet of paper.

- - - - - - - - - - -

$R = \frac{E}{I}$ Solution: $E = IR$

Divide each side by I to isolate R.

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

$$\frac{E}{I} = R, \text{ or}$$

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

24. Refer again to Figure 3-2. The battery produces 6 v. and the current in the circuit is 2 a. What is the resistance of the lamp? ______________

\- - - - - - - - - - -

$$R = \frac{E}{I} = \frac{6 \text{ v.}}{2 \text{ a.}} = 3\,\Omega$$

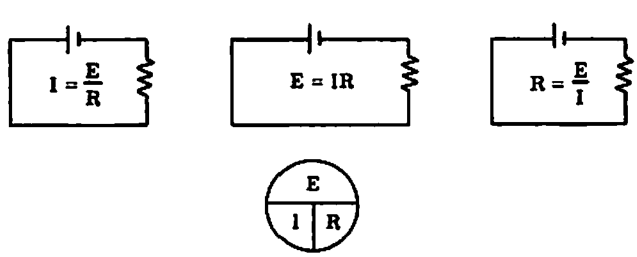
25. A 12-volt battery produces a current in the circuit of 0.5 a. What is the resistance? __________

\- - - - - - - - - - -

$$R = \frac{E}{I} = \frac{12 \text{ v.}}{0.5 \text{ a.}} = 24\,\Omega$$

(Note: The circuit values in these exercises are selected for easy calculation.)

26. You have now used Ohm's Law to solve for all three circuit values: voltage (E), current (I), and resistance (R). It is important to note that resistance (R) is a physical constant. The value of resistance cannot be changed by changing voltage (E) or current (I). Here is an aid to remembering the three basic equations:

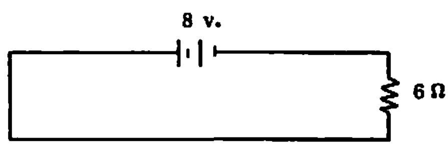


In the preceding circle, cover up the value you wish to solve for, and the rest of the equation is revealed. For example, $I = \frac{E}{R}$. Write the equations for E and for R using the memory aid.

- - - - - - - - - -

$E = IR$; $R = E/I$

27. A lamp or any other component has resistance. If the purpose of the schematic is to work out relationships among current, voltage, and resistance, the symbol for a resistor may be used instead of that for the actual component. How much current is flowing in this circuit? ______



- - - - - - - - - -

1.33 a. (Note: It would be more accurate to say $1\frac{1}{3}$ a., but values are usually given in decimals.)

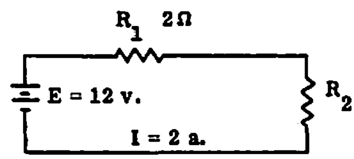
28. Draw the schematic symbol for a resistor. ________________

- - - - - - - - - -

 (Note: Its position does not matter.)

29. The schematic symbol in frame 28 is actually the symbol for a <u>resistance</u> rather than for a resistor only. Any device that consumes power is a resistance. The resistor, which is manufactured to precise specifications and whose function is to limit current, is a resistance, but so is a lamp, an electric iron, or a warming tray. These devices do limit current, and are therefore resistances, but each has a function besides current limiting. When we show the symbol for a resistance in this book, we usually call it a resistor; but remember that the symbol could mean some other kind of resistance.

Of course, the circuit might include more than one resistor. If so, the resistors are usually labeled R_1, R_2, etc., with their respective values. Resistors in series are merely added to get the total resistance. We shall see why this is true later. In the following drawing, what is the value of R_2? __________



- - - - - - - - - - -

$R_2 = 4\ \Omega$ Solution: $R = \frac{E}{I} = 6$

$R_1 = 2\ \Omega$

$R_2 = 6 - 2 = 4\ \Omega$

30. Without changing the resistors in the circuit, how could you increase the current to 4 a.? ____________________

- - - - - - - - - - -

Substitute a 24-volt battery for the 12-volt battery.

Solution: $E = IR = 4 \times 6 = 24$

If you need a rest, this is a good place to stop.

Power

31. Perhaps you have noticed a wheel in your home power-meter that turns when electricity is being used. If the main switch is off, the wheel is at rest, because no power is being consumed. As more lights and appliances draw current, the wheel turns faster. Power, whether electrical or mechanical, pertains to the rate at which work is done, so the power consumption in your home is related to current flow. (You will learn the exact relationship later.) An electric range or dryer consumes more power (and draws more current) in a given length of time than a reading lamp, for example, because more current is required to produce heat than to produce light. (Of course, every device produces some heat.) The ampere is a measure of the rate at which current flows. Power is the

____________________ at which work is done.

- - - - - - - - - - -

rate

32. You might say that an electric range does more work than a reading lamp, but this is true only if the time both appliances are used is the same. If you read a lot and send your clothes to the laundry, your reading lamp could do more work in a year than your dryer. In considering power, we are not concerned with the total amount of work done but the rate at which

it is done. Work is done whenever a force causes motion—even the movement of electrons through a conductor. A dryer uses more current in a given length of time than a reading lamp, so its power consumption is greater. State in your own words what it means to say that a dryer consumes more power than a reading lamp. (Hint: Relate your answer to current flow.) ______________________________

____

- - - - - - - - - -

A dryer uses more current in a given length of time than a reading lamp.

33. If a compressed spring is held in place between two fixed points, a force is exerted on those points, but no work is done. Similarly, if a switch is opened in an electric circuit, a force (difference in potential) exists, but no work is done because no current flows. When the switch is closed, a circuit is completed, current flows, and some kind of work is done; a lamp is lit, perhaps. Only then are we concerned with power. Power is used only in a(n) (open/closed) ______________ electric circuit.

- - - - - - - - - -

closed

34. The basic unit of power, or the rate at which work is done, is the watt. Just as current is measured in amperes, power is measured in ________.

- - - - - - - - - -

watts (Note: "Watt" is abbreviated "w.")

35. Power (P) is directly related to the voltage (E) across a circuit and the current (I) flowing in the circuit. One watt represents the amount of power consumed when the difference in potential of one volt produces a current of one ampere. Power (P) is equal to voltage (E) multiplied by current (I). Write the equation that states this mathematically.

____

- - - - - - - - - -

$P = EI$ (or $P = E \times I$)

36. A 10-volt battery is the voltage source for a circuit whose total resistance is 5Ω. Before you can solve for the power in the circuit, you must first solve for ______________.

- - - - - - - - - -

current (I) (Note: Later you will be able to solve for power when voltage and resistance are given.)

37. What is the equation for current when voltage and resistance are given?

____

- - - - - - - - - -

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

38. What is the current in the circuit described in Frame 36? ___________

- - - - - - - - - -

2 a.

39. What is the equation for power (P) when voltage (E) and current (I) are given? ______________________

- - - - - - - - - -

P = EI

40. What is the power in the circuit described in Frame 36? ___________

- - - - - - - - - -

20 w.

41. In Frame 36, E and R were given. But because you knew only the power equation, P = EI, you had to solve for I before you could arrive at P. There is, of course, a short cut.

(1) P = EI

(2) Substitute the equivalent of I in terms of E and R. You can do this, since you know that $I = \frac{E}{R}$.

(3) $P = E\left(\frac{E}{R}\right)$

(4) $P = \frac{E^2}{R}$

If the voltage in a given circuit is 4 v. and the resistance is 4Ω, what is the power? (Use the equation just developed.) _________

- - - - - - - - - -

$$P = \frac{E^2}{R}$$
$$= \frac{4^2}{4}$$
$$= \frac{16}{4}$$
$$= 4 \text{ w.}$$

42. The circuit voltage is 2 v. and the resistance is 12Ω. What is the power?

____

- - - - - - - - - -

$\frac{1}{3}$ w. (0.33 w.)

43. E = 3; R = 2.

P = __________

- - - - - - - - - -

4.5 w.

44. You can work the mathematics for power when current and resistance are given, without solving first for voltage.

(1) P = EI

(2) Substitute the equivalent of E in terms of I and R. Remember that E = IR.

(3) P = IR(I)

(4) $P = I^2R$

If the current in a given circuit is 4 a. and the resistance is 10Ω, what is the power? __________

- - - - - - - - - -

$$P = I^2R$$
$$= 4^2 \times 10$$
$$= 16 \times 10$$
$$= 160 \text{ w.}$$

45. The circuit current is 0.5 a. and the resistance is 12Ω. What is the power? __________

- - - - - - - - - -

3 w.

46. $I = 4$ a.; $R = 2\Omega$.

$P =$ __________

\- - - - - - - - - - -

32 w.

47. Write the equation for P when E and I are given. __________________

\- - - - - - - - - - -

$P = EI$

48. Write the equation for P when E and R are given. __________________

\- - - - - - - - - - -

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

49. Write the equation for P when I and R are given. __________________

\- - - - - - - - - - -

$P = I^2 R$

You probably know that an electric dryer or stove requires a higher voltage than most other appliances in the home. The conversion of electrical energy into heat uses much more current than a radio or electric drill, for example, so some devices require more voltage—and heavier wiring to protect them from damage. Power calculations are quite important in advanced electricity and electronics, but one important application of power theory is discussed in the next section.

If you plan to take a break pretty soon, do it now.

Rating of Electrical Devices by Power

50. When you replace a burned-out light bulb, how do you decide which new bulb to select as a replacement? ______________________________

____

\- - - - - - - - - - -

You look on the bulb to read its wattage.

51. Light bulbs, soldering irons, and motors are a few of the electrical devices that are rated in watts. The wattage rating of a device indicates the rate at which the device converts electrical energy into some other form of energy, such as heat, light, or motion. An electric lamp converts electrical energy into ______________________.

\- - - - - - - - - -

light (Note: Some energy is converted into heat, because the lamp is not 100 percent efficient.)

52. In the kitchen, electrical energy is converted into light or into mechanical energy (in the case of a blender, for example). If you have an electric range, electrical energy is also converted into ____________________.

\- - - - - - - - - -

heat

53. The greater the wattage of an electrical device, the greater the rate at which electrical energy is converted to another form. A 100-watt bulb produces more light than a (50/150) _________ -watt bulb.

\- - - - - - - - - -

50

54. A soldering iron converts electrical energy into heat. Soldering irons are rated in watts. State in your own words the difference between a 300-watt and a 500-watt soldering iron. ________________________________

____

\- - - - - - - - - -

The 500-watt iron draws more current and produces more heat.

55. Since power is related to voltage, current, and resistance, electrical devices produce their rated power only if they are operated at the correct circuit values. In a home electrical circuit, only the (current/voltage/resistance) ______________________ is constant.

\- - - - - - - - - -

voltage

56. Electrical devices are rated for voltage as well as wattage (power). A device will draw the proper amount of current only if the correct voltage is applied. A light bulb, for example, is designed to produce a certain

amount of light. To do so, it must be operated at a voltage that will result in the right amount of current, and the proper power consumption, to produce that much light. If the applied voltage is too low, the light will be dimmer than is desired. If too much voltage is applied, the light will be brighter, and it will probably burn out, because it draws too much current for its filament to withstand safely. A light bulb is labeled with its wattage, such as 100 w., and also with its proper voltage, which is usually 115 v. (standard house voltage). If a 115-volt lamp is plugged into a

230-volt circuit, what happens to the current? ____________________

- - - - - - - - - -

It doubles.

57. Let's see how this wattage and voltage rating works. A 100-watt lamp is rated for 110 v. When it is turned on, how much current flows in its circuit? (Hint: Remember the equation, $P = EI$.) In this and other problems, you may round off your answer to two decimal places for simplicity.

____

- - - - - - - - - -

0.91 a. Solution: $P = EI$

$$\frac{P}{E} = \frac{EI}{E}$$

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

$$I = \frac{P}{E} = \frac{100}{110} = 0.909$$

58. If the same 100-watt lamp is plugged into a 220-volt circuit, how much current flows? (Hint: Calculate the resistance of the filament from

Frame 57.) __________

- - - - - - - - - -

1.82 a.

59. How much power is now consumed by the lamp? (Hint: The lamp is rated at 100 w., but it could consume much more power momentarily before it

burns out. $E = 220$; $I = 1.82$.) __________

- - - - - - - - - -

400.4 w.

Note that the power did not merely double when the circuit voltage was doubled. The power quadrupled. (The answer was not exactly 400 w. because some values had been rounded off earlier.) That is because not only the voltage but the current doubled. The bulb would probably burn out when the lamp is plugged into the 220-volt circuit. Its life would certainly be shortened. If the normal wattage rating of a device is exceeded (by using an incorrect voltage), it will overheat and will probably suffer damage. Now let's see how electrical devices are rated to prevent damage.

Power Capacity of Electrical Devices

60. The wattage rating of a light bulb indicates its ability to do work. A 100-watt light bulb, for example, is expected to produce a certain amount of light when it is used in its normal circuit. However, the wattage rating of some devices indicates operating limits. A resistor is one such device. It is designed to be used in circuits with widely varying voltages, depending on the desired current. But each resistor has a maximum current limitation for each voltage applied. The product of the voltage drop across a resistor and the current through it (the result when these values are multiplied) must not exceed a certain wattage, since this wattage indicates the maximum safe power consumption. (Remember, P = EI.) A 10-watt resistor subject to 10 v. has a maximum current limitation of 1 a. because this combination of voltage and current results in a power consumption of 10 w. If the voltage across the resistor is increased, less current is needed to produce the same power, so the maximum current limitation of the resistor will be less. If the voltage across our 10-watt resistor is 20 v., what is the maximum current that can safely flow through the resistor without damage? __________

\- - - - - - - - - - -

0.5 a.

61. All the resistors in Figure 3-3 are labeled with their wattage rating.

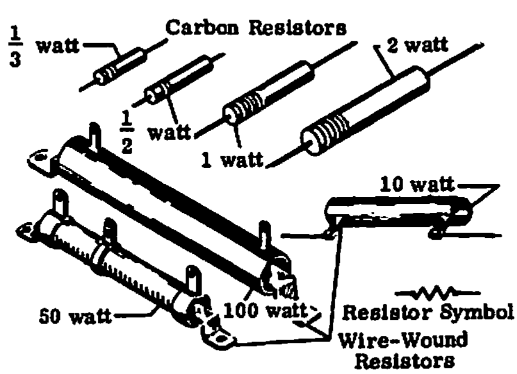


Figure 3-3. Resistors of different wattage ratings.

Small resistors are color-coded for these values; larger resistors are stamped with their resistance in ohms. The two most common types are carbon resistors and wire-wound resistors. Resistors rated at 2 w. and under are usually carbon resistors. What type of resistors are used for higher wattage ratings? ____________________

- - - - - - - - - -

wire-wound

62. From your examination of the carbon resistors in Figure 3-3, what can you say about the relationship of the size of a resistor to its wattage rating? ____

- - - - - - - - - -

Something like: The larger the resistor, the higher its wattage.

63. Resistors with ratings of 2 watts or less are generally carbon, while wire-wound resistors are usually made in ranges of 2 to 200 watts. (Resistors with higher wattage ratings are of special construction.) Opposite the ratings shown below, indicate the probable construction of a resistor with that rating.

$\frac{1}{2}$ w. __________	50 w. __________
1 w. __________	150 w. __________

- - - - - - - - - -

$\frac{1}{2}$ w., carbon; 1 w., carbon; 50 w., wire-wound; 150 w., wire-wound.

64. When current passes through a resistor, electric energy is transformed into heat, which raises the temperature of the resistor. If the temperature becomes too high, the resistor may be damaged. In a wire-wound resistor, the metal wire may melt, opening the circuit and interrupting current flow. This effect is used in devices that protect household (and other) electrical circuits from overloading. From your own experience, what do you think these devices are? (Hint: They will "blow" if too many appliances are plugged into the same outlet.) ____________________

- - - - - - - - - -

Fuses

65. Figure 3-4, on the following page, includes the symbol for a fuse. It is labeled F_1.

Look at the figure, then draw the schematic symbol for a fuse.

____

- - - - - - - - - -

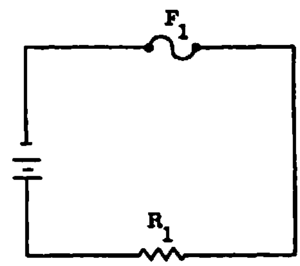


Figure 3-4. Simple circuit that includes a fuse and a resistor.

66. Fuses are actually metal resistors with very low resistance values. They are designed to "blow" when the current exceeds a certain value. A circuit that includes a resistor and a fuse is shown in Figure 3-4. Must the current that flows through the resistor also flow through the fuse? ____

- - - - - - - - - - -

yes

67. The fuse (F_1) in Figure 3-4 is rated at 0.5 a. and has a resistance of 1Ω. R_1 has a value of 29Ω. The applied voltage is 6 v. What is the current in the circuit? ________

- - - - - - - - - - -

0.2 a. $\left(I = \frac{E}{R} = \frac{6}{29 + 1} = 0.2\right)$

68. Will the fuse blow? (Yes/No) _______, because ____________________
____.

- - - - - - - - - - -

No, because the current is less than the rated value for the fuse (which is 0.5 a.).

69. If R_1 in Figure 3-4 has a value of 7Ω and the voltage remains unchanged (6 v.), what is the circuit current? ________

- - - - - - - - - - -

0.75 a. $(6 \div 8 = 0.75)$

70. Will the fuse blow? Explain. ______________________________

- - - - - - - - - - -

Yes, because the current now exceeds the rated value of the fuse. (Note: The fuse will blow when the current exceeds 0.5 a. The current is now 0.75, or 50 percent over maximum.)

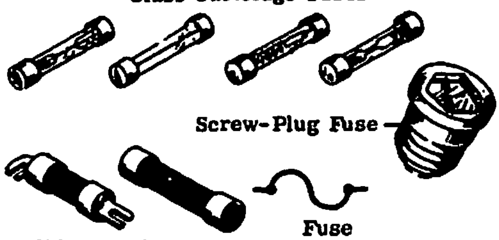


Figure 3-5. Typical fuse types.

Figure 3-5 shows some typical types of fuses. The screw-plug fuse is commonly used for most house circuits, but solid cartridge fuses are used for heavier-duty circuits such as those for the kitchen range and the clothes dryer. Automobile accessory circuits, such as the radio, usually have glass cartridge fuses. Circuit breakers, which are merely reset, are now becoming more and more common. The breaker is "thrown" when the current exceeds the rated value for the circuit breaker.

A subject closely related to power is energy, the subject of the next section.

Energy

So far in this chapter we have dealt with two basic concepts—current flow and power. Before we move on to still another related concept—energy—it might be a good idea to tie together the material covered so far.

All three values included in Ohm's Law (voltage, current, and resistance) are related to one thing: current. Voltage is the "pressure" that causes current to flow, and resistance is the factor that limits the current flow when voltage of a given value is applied.

Power, too, is related to current, because no work is done (and therefore, no power is consumed) unless there is current flow. All of the power equations involve current. Either current (I) is directly included in the equation, or it affects the other values (E and R) in the equation.

Thus, Ohm's Law deals directly with current and the other variables that affect it (E and R), while power is directly related to the current flow in a circuit.

71. Energy is defined as the ability to do work. When the archer draws the bow string, for example, the ability to do work is present, but no work is done until the arrow is released. Then the potential for work (energy) is converted to work actually done (power consumption). Energy is expended when work is done, because it takes energy to maintain a force when that force does work. In electricity, energy (W) is equal to the rate at which work is done, or power (P), multiplied by the length of time (t) the rate is measured. Circle the equation below that expresses this mathematically.

$$P = Wt$$

$$W = Pt$$

$$P = \frac{W}{t}$$

- - - - - - - - - - -

W = Pt

72. The symbol for energy, W, comes from "watt." Remember that energy is the rate at which work is done, and "rate" implies a time. Miles per hour and feet per second are both rates. In electricity, W will be in watt-hours if time (t) is in hours. If it is expressed in seconds, W will be in

______________________.

- - - - - - - - - - -

watt-seconds (Note: Watt-seconds means "watts per second" or "watts times seconds.")

73. An hour is usually too large a measure for calculations in electricity. The second is much more convenient. Let's return for a moment to our basic power equation, P = EI. Assume a very simple circuit in which a 1-volt battery causes current flow of 1 a. P = _____ x _____, or _____ w.

- - - - - - - - - - -

P = 1 v. x 1 a., or 1 w.

74. Power is consumed in the circuit only while current is flowing. Since 1 a. of current flowed with 1 v. applied to the circuit, the power consumed was 1 w. But how much energy was responsible for that amount of power consumption in one second? Simply apply the energy equation, W = Pt. The energy, or rate at which work is done, is 1 ___________ - ___________.

- - - - - - - - - - -

watt-second

75. Another term for "watt-second" is joule, pronounced "jule." In a given circuit, W is calculated to be 300 watt-seconds. Another way to express W in this circuit is 300 ________________.

- - - - - - - - - -

joules

76. You are billed for energy used in your house by kilowatt-hours. ("Kilo" is a prefix that means 1,000; thus, one kilowatt is equal to 1,000 watts.) Just for fun, assume your electric bill shows that you used 10 kilowatt-hours and translate this figure into joules. ____________________

- - - - - - - - - -

36,000,000 joules, or 36,000 kilo-joules, or 36 mega-joules
(10 x 1,000 x 60 x 60 = 36,000,000)

77. A 10-volt circuit has a total resistance of 4Ω, and current flows for 2 seconds. P = ________

- - - - - - - - - -

$$P = \frac{E^2}{R} = \frac{10^2}{4} = \frac{100}{4} = 25 \text{ w.}$$

78. In the circuit described in Frame 77, W = ________.

- - - - - - - - - -

W = Pt = 25 x 2 = 50 joules (watt-seconds)

79. E = 20 v.; I = 4 a.; t = 3 seconds.

P = ________ W = ________

- - - - - - - - - -

P = 80 w.; W = 240 joules

80. E = 15 v.; I = 6 a.; t = 2 seconds.

P = ________ W = ________

- - - - - - - - - -

P = 90 w.; W = 180 joules

81. I = 6 a.; R = 2Ω; t = 4 seconds.

W = ________

- - - - - - - - - -

W = 288 joules   ($P = I^2R$; W = Pt)

82. Figure 3-6 shows the schematic diagram of an unknown device, represented electrically by a single resistor, R_2, enclosed in a dashed-line box. Device X actually consists of several components, but we are interested only in its total resistance. If you can solve for current, power, and energy, you understand the essential concepts presented in this chapter.

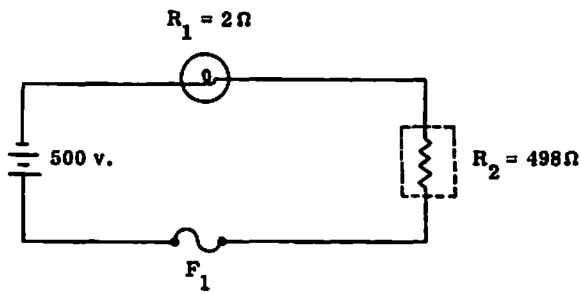


Figure 3-6. Schematic diagram of Device X.

The light, R_1, indicates when the device is running. A timer in Device X opens the switch 5 seconds after power is applied. When the device shuts off, a button must be pressed to restart it.

Assume for simplicity that the fuse and wiring have no resistance.

1. Total current flow is ________.
2. Power consumed during the running time of Device X is _____.
3. The energy developed in the circuit is _________.

- - - - - - - - - -

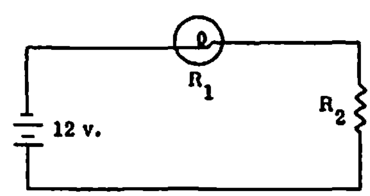
1. I = 1 a. (500 v. ÷ 500 Ω)
2. P = 500 w. (500 v. x 1 a.)
3. W = 2500 watt-seconds, or joules. (500 w. x 5 seconds)

You have learned to apply Ohm's Law to solve for voltage, current, and resistance. You have built on that basic information to solve for power consumption and energy in a simple electric circuit. You have also become aware that electrical devices can be damaged if the power consumption is beyond their capacity. And you have begun to use the schematic symbols and equations that will be your shorthand as we go further into electrical theory. Now proceed to the Self-Test.

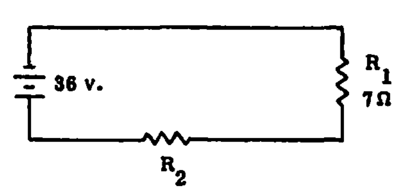
Self-Test

The following questions will test your understanding of Chapter Three. Write your answers on a separate sheet of paper and check them with the answers provided following the test.

1. Draw a schematic diagram of an electric circuit that includes (a) a battery, (b) a resistor, (c) a lamp, (d) a fuse, and (e) a switch in the open position. Show the battery connected so that current would flow counterclockwise in the circuit. Label the battery terminals (+) and (–).
2. Complete these equations, which are developed from Ohm's Law.
   (a) I = ?   (b) E = ?   (c) R = ?
3. Refer to the schematic diagram to solve the following problems.



   (a) $R_1 = 3\,\Omega$; $R_2 = 9\,\Omega$. I = ?
   (b) $R_1 = 5\,\Omega$; I = 2a. R_2 = ?
   (c) $R_1 = 7\,\Omega$; $R_2 = 25\,\Omega$. To produce a current of 0.75 a., remove the 12-volt battery and replace it with a battery of how many volts?
4. Write the power equation for each set of known values listed: (a) Voltage and current are known; (b) Voltage and resistance are known; (c) Current and resistance are known.
5. Write the equation for energy when power and time are known.
6. Refer to the schematic diagram to solve the following problems.



   (a) P = ?
   (b) The current flows for 3 seconds before the circuit is opened. W = ?
   (c) How much energy will be developed in the circuit if a 24-volt battery is substituted for the 36-volt battery and current flows for 3 seconds?

7. How much current is used to illuminate a 100-watt light bulb rated at 115 v.?

8. A resistor rated at 2 watts is probably wire-wound or carbon?

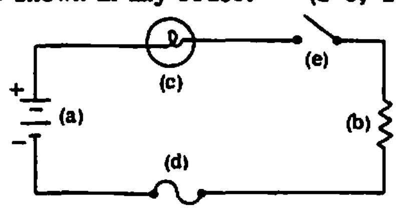
9. Name two devices used to protect circuits from overloads.

10. What is the difference between power and energy in an electric circuit?

Answers

If your answers do not agree with those below, review the frames in parentheses before going on to the next chapter.

1. Here is one possibility. The negative side of the battery is a shorter line. Your battery can have any number of pairs of lines. The other schematic symbols may be shown in any order. (1-8, 27-29, 65)



2. (a) $I = \frac{E}{R}$ (13)
   (b) $E = IR$ (18)
   (c) $R = \frac{E}{I}$ (23)

3. (a) I = 1a. (14)
   (b) $R_2 = 1\Omega$ (25)
   (c) 24 (30)

4. (a) $P = EI$ (35)
   (b) $P = \frac{E^2}{R}$ (41)
   (c) $P = I^2R$ (44)

5. $W = Pt$

6. (a) 81 w. You could have used $P = \frac{E^2}{R}$; or, solving for current first, $P = EI$. (41)
   (b) 243 joules (or watt-seconds) (78)
   (c) 108 joules (78)

7. 0.87 a. ($P = EI$; $I = \frac{P}{E}$) (57)

8. carbon (61)

9. Circuit breakers and fuses (66)

10. Power is the rate at which work is done, while energy is the ability to do work. (31, 71)

CHAPTER FOUR
Series and Parallel Circuits

In Chapter Three you learned Ohm's Law, which is fundamental in electricity. You became familiar with some basic circuit components (battery, lamp, resistor, switch, fuse) and their schematic symbols, and you learned to solve problems involving voltage, current, resistance, power, and energy.

When you finish this chapter you will know how to:

- apply Kirchhoff's Law of Voltages to series circuits;
- apply Ohm's Law to solve for values in parallel circuits;
- apply Kirchhoff's Current Law to solve for current flow in parallel circuits;
- distinguish between series and parallel circuits;
- solve for total resistance in parallel circuits; and
- trace a circuit to establish the polarities of voltages.

Series Circuits

1. In the circuits listed in Chapter Three, you probably noticed that the same current in the circuit flowed through each component, such as a resistor, lamp, or fuse, in that circuit. Those circuits were series circuits. Thus, you could define a series circuit as a circuit in which the current has

   (only one/more than one) ____________________ path.

   \- - - - - - - - - -

   only one

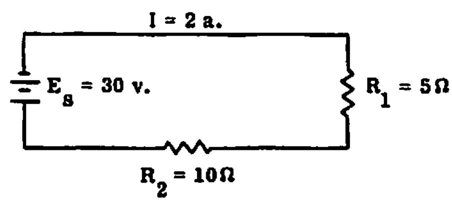
2. You also learned that current cannot flow in an open circuit, since there is no complete path for the current. If a light bulb burns out, its filament breaks, and interrupts the circuit. In strings of old-fashioned Christmas tree lights (and some of the less-expensive lights available today), if one bulb burns out, all lights on the string go out. The lights in such a string

   are part of a ____________________ circuit.

   \- - - - - - - - - -

   series

3. So far you have solved problems involving source voltage only. But when current flows through any device (sometimes called "load") that has resistance, we say that a voltage is "dropped" across the device. (The term "drop" is used because, when voltage is developed in one location, there is a drop in the voltage available at other locations.) In each case, you can calculate the amount of voltage that is dropped across a device if you know its resistance and the current flowing through it, using the formula E = IR that you already know. In the circuit below, solve for the voltage drops across the two resistors.



$E_{R_1} = I \times R_1 = 2\text{ a.} \times 5\Omega = 10\text{ v.}$

E_{R_2} = ________

\- - - - - - - - - -

$E_{R_2} = 20$ v. Solution: $E_{R_2} = I \times R_2 = 2\text{ a.} \times 10\Omega = 20\text{ v.}$

4. The source voltage (E_s) in the circuit is 30 v..

$E_{R_1} + E_{R_2}$ = ________

\- - - - - - - - - -

30 v.

5. From Frame 4 we can deduce (though we won't prove it here) that the total of all voltage drops in a series circuit is equal to the ____________.

\- - - - - - - - - -

source voltage

6. Kirchhoff's Law of Voltages states this truth in different words: <u>The algebraic sum of all the voltages in any complete electric circuit is equal to zero.</u> In a circuit that includes three resistors, there will be a source voltage (E_s) and three voltage drops in the circuit.

To demonstrate:

$E_s = E_1 + E_2 + E_3$

Transposing everything to the left side of the equation:

$E_s - E_1 - E_2 - E_3 = 0.$

This is called the algebraic sum of the terms. In other words, the sum of all positive voltages must be equal to the sum of all __________ voltages.

- - - - - - - - - -

negative

7. For any voltage rise there must be an equal voltage drop somewhere in the circuit. The voltage rise (potential source) is usually regarded as the power supply, such as a battery. The voltage drop is usually regarded as the voltage across a load, such as a resistor. The voltage drop may be distributed across a number of resistive elements, such as a string of lamps or several resistors. However, according to Kirchhoff's Law, the sum of their individual voltage drops must always equal the voltage rise supplied by the power source. In the circuit diagram in Frame 3, the source voltage is 30 v. The voltage drop across R_1 is 10 v., and the voltage drop across R_2 is 20 v. The total voltage drop across the two resistors is 30 v., which is the same as ______________________________.

- - - - - - - - - -

the source voltage

8. If R_1 is taken out of the circuit (and its connecting wires joined), the current will increase because the circuit resistance is lower. You could apply Ohm's Law ($I = \frac{E}{R}$) to find the current, then apply another Ohm's Law equation ($E = IR$) to find out the voltage drop across R_2, or E_{R_2}. In this case, however, we don't need to do that, because there is only one resistor in the circuit. Applying Kirchhoff's Law of Voltages instead, we know immediately that E_{R_2} is 30 v. Why? ______________________

- - - - - - - - - -

Because the source voltage is 30 v.

9. In your own words, state the relationship between all the voltage drops in a series circuit and the source voltage. ______________________

____

- - - - - - - - - -

The total of all voltage drops is equal to the source voltage.

10. In a circuit whose source voltage is 12 v. and in which there are only two resistors, there is a voltage drop of 10 v. across one resistor. How much voltage is dropped across the other resistor? __________

\- - - - - - - - - -

2 v.   (12 − 10)

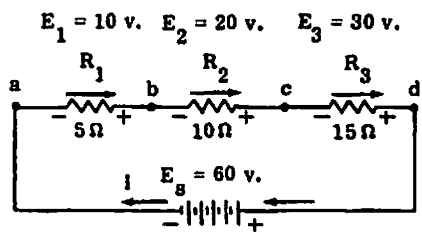


Figure 4-1. Series circuit for demonstrating Kirchhoff's Law of Voltages.

Refer to Figure 4-1 for frames 11 through 20.

11. The "positiveness" or "negativeness" of a value in electricity is called polarity. Whenever there is a difference in potential between two points, such as the two terminals of a battery or the two ends of a resistor, one point is always positive (+) with respect to the other point, which is negative (−). Polarity cannot be assigned to a single point unless that point is compared with some other point. For convenience in understanding the schematic in Figure 4-1, certain points are labeled a, b, c, and d. Look at point b; it is positive with respect to point a but negative with respect to point c. In electricity, we are often interested in the polarity of a difference in potential. Certain devices are designed to be placed in a circuit in a specific way and will not work properly if the polarity is reversed. In troubleshooting electric circuits, the technician often needs to know whether a given difference in potential is positive or negative. E_1, the voltage drop across R_1, is 10 v. This represents a difference in potential of 10 v. between which two points labeled in the circuit? __________

\- - - - - - - - - -

a and b

12. We have not yet assigned a polarity to the difference in potential. We will learn how to do this in a little while, but first let us review voltage drops and current flow. Remember that a voltage drop is a difference in potential. What is the voltage drop between points c and d? __________

\- - - - - - - - - -

30 v.

13. What is the voltage drop between points a and c? (Hint: Add E_1 and E_2.)

____

\- - - - - - - - - -

30 v.

14. You have been reminded from time to time that current flows from negative to positive. You have another reminder in Figure 4-1, since arrows show the direction of current flow. The current flow through R_1 is from point _____ to point _____.

\- - - - - - - - - -

point a to point b

15. To establish the polarity of a difference in potential, a convention has been established that neatly fits the algebraic terms of Kirchhoff's Law of Voltages. Start at any point in a complete circuit and, following the direction of the current flow, label the ends of all loads as positive or negative. (A load is any device outside the power supply, such as a resistor or lamp, across which there is a difference in potential.) There is also a difference in potential across a power supply, and its terminals are labeled (+) and (–). Go around the circuit only once and be sure to trace the circuit in the direction of current flow. The first point of a load, such as R_1, encountered by the current is labeled (–). The other side of that load is labeled (+). The end of R_1 in Figure 4-1 encountered second as you trace the circuit is labeled (–/+) ______.

\- - - - - - - - - -

\+

16. The end of R_2 first encountered as you trace the circuit in the direction of current flow is labeled (–/+) ______.

\- - - - - - - - - -

–

17. A question may have occurred to you at this point: Since the right end of R_1 and the left end of R_2 in Figure 4-1 are electrically the same, why is one point labeled (+) and the other (–)? It is because we are interested in the polarity of the voltage across a load, not in the polarity (positive or negative) of a single point. By labeling the polarity of the first point encountered when a load is reached, the polarity of the voltage drop across the load can be established. Since the first point encountered when you

reach R_1 is negative, E_1 is −10 v. E_2 is (−20/+20) ________ v.

- - - - - - - - - -

-20

18. In all work with direct-current electricity, you should label each voltage as either (+) or (−). What is the voltage drop across R_3? ______

- - - - - - - - - -

−30 v.

19. What is the voltage drop across E_s? ________

- - - - - - - - - -

+60 v. (The first point encountered in tracing the circuit is the positive terminal of the battery.)

20. You can see that the labeling of loads described above is consistent with Kirchhoff's Law of Voltages:

$$E_s + E_1 + E_2 + E_3 = 0$$
$$(+60) + (-10) + (-20) + (-30) =$$
$$+60 - 10 - 20 - 30 = 0$$

The algebraic sum of all the voltages in any complete electric circuit is equal to _____.

- - - - - - - - - -

zero

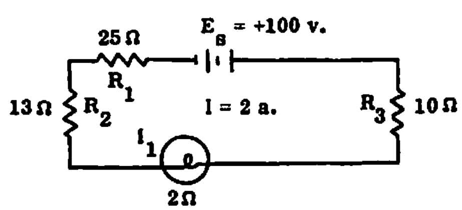


Figure 4-2. A simple DC circuit.

Refer to Figure 4-2 for Frames 21 through 25.

21. A resistor is designated R. What letter designates a lamp? ______

- - - - - - - - - -

I (Note: Don't be confused by the fact that, in equations, I means current. When a schematic symbol is labeled I, usually with a subscript, it means lamp. Memory aid: I stands for "Incandescent.")

22. Current flow is from E_s toward ________. (Hint: Remember that the short side of the battery symbol indicates the negative terminal.)

- - - - - - - - - - -

R_1

23. Label both ends of each load with the proper symbol of polarity (+ or −); then calculate the following voltage drops. (Remember that the current is the same throughout the circuit.)

$E_{R_1} = ?$ $E_{R_3} = ?$

$E_{R_2} = ?$ $E_{I_1} = ?$

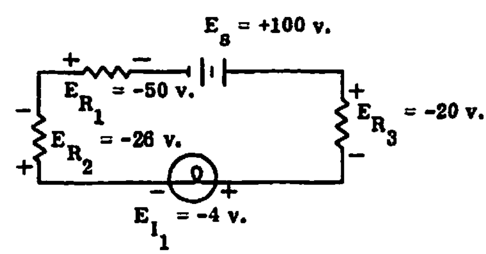
- - - - - - - - - - -

$E_{R_1} = -50$ v. ($E = IR$)

$E_{R_2} = -26$ v.

$E_{R_3} = -20$ v.

$E_{I_1} = -4$ v.



24. What is the sum of the voltage drops across all loads in the circuit outside the battery? ________

- - - - - - - - - - -

−100 v.

25. The total voltage drop across all loads in a circuit is the same as the

______________________________.

- - - - - - - - - - -

source voltage, or power supply (But the polarity is opposite.)

26. From now on, we're going to simplify things a bit. Ignore polarity for this series of frames. Polarities of voltage drops are usually omitted in this book unless they are needed to demonstrate Kirchhoff's Law of Voltages. In many applications in general practice, however, it is necess-

ary to assign polarities. Unlike the practice in algebra, the absence of a sign does not mean (+). Note that we are also simplifying the designations of voltage drops. E_1 is the same as E_{R_1}, E_2 is E_{R_2}, etc. The more complicated subscript is useful, however, when different types of components, such as resistors and lamps, are used as loads. Study Figure 4-3 below and then solve for the voltage drops.

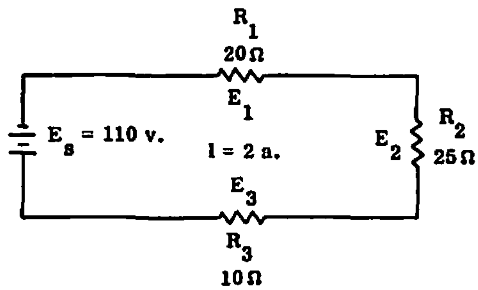


Figure 4-3. Series circuit with three resistors.

Refer to Figure 4-3 for Frames 26 through 39.

E_1 = ________

E_2 = ________

E_3 = ________

- - - - - - - - - - -

E_1 = 40 v. (E = IR)

E_2 = 50 v.

E_3 = 20 v.

27. What is the total voltage drop across all three resistors? ________

- - - - - - - - - - -

110 v.

28. You can establish an equation for the source voltage and all the individual voltage drops in the circuit:

E_s = _____ + _____ + _____

- - - - - - - - - - -

$E_s = E_1 + E_2 + E_3$

29. To find each voltage drop, you had to apply Ohm's Law, $E = IR$. You knew the total circuit current, which was the same at all points in the series circuit, and you knew each value of resistance. You could have written a variation of the equation in Frame 28:

$$E_s = IR_1 + \_\_\_\_\_ + \_\_\_\_\_$$

- - - - - - - - - - -

$E_s = IR_1 + IR_2 + IR_3$

30. R_t is the designation for total circuit resistance. Applying Ohm's Law,

$E_s = I\_\_\_\_\_.$

- - - - - - - - - - -

$E_s = IR_t$

31. Substituting IR_t for E_s, you can write an equation for the source voltage and all the voltage drops in the circuit in terms of I and R:

$$IR_t = \_\_\_\_\_ + \_\_\_\_\_ + \_\_\_\_\_$$

- - - - - - - - - - -

$IR_t = IR_1 + IR_2 + IR_3$

32. Thus, you see that E_s can be expressed in terms of circuit current and total circuit resistance: $IR_t = IR_1 + IR_2 + IR_3$. Since there is only one path for current in a series circuit, the total current is the same in all parts of the circuit. Dividing both sides of the voltage equation by the common factor, I, an expression is derived for the total resistance of the circuit:

$$IR_t = IR_1 + IR_2 + IR_3$$

Divide through by I.

$$R_t = \_\_\_\_\_ + \_\_\_\_\_ + \_\_\_\_\_$$

- - - - - - - - - - -

$R_t = R_1 + R_2 + R_3$

33. To find the total resistance, R_t, substitute the resistance values in Figure 4-3 and solve for R_t. ______________________________

- - - - - - - - - - -

$R_t = 20\Omega + 25\Omega + 10\Omega = 55\Omega$

34. State in your own words the relationship between total circuit resistance and the individual resistances in a series circuit. ________________

____

- - - - - - - - - -

The total resistance is the sum of the resistances of the individual parts of the circuit.

35. In Figure 4-3, the total resistance is 20 + 25 + 10 = 55Ω. You can prove this by applying Ohm's Law. E_t designates the total of all voltage drops in the circuit. I_t is 2 a. Using the basic resistance equation ($R = \frac{E}{I}$), solve for R_t. ________

- - - - - - - - - -

$$R_t = \frac{E_t}{I_t}$$

$$= \frac{40 + 50 + 20}{2} = \frac{110}{2}$$

$$= 55\Omega$$

36. Now let's solve some power problems using known values from Figure 4-3. The power equation to be used when resistance and current are known is $P = I^2R$. Applying this equation to R_1 in Figure 4-3, we have $P = 2^2 \times 20 = 4 \times 20 = 80$ w., the power absorbed by R_1. How much power is absorbed by R_2? ________

- - - - - - - - - -

100 w. ($2^2 \times 25$)

37. How much power is absorbed by R_3? ________

- - - - - - - - - -

40 w.

38. What is the total power absorbed by the three resistors in Figure 4-3?

____

- - - - - - - - - -

220 w. (You may either add separate power values, or add the resistances and use the equation $P = I^2R$.)

39. Since you know the circuit current and the total of the voltage drops in the circuit, you could have applied another power equation, P = EI, or in this case, $P_t = E_t I_t$.

P_t = ______ x ______ = ______ w.

- - - - - - - - - - -

P_t = 110 x 2 = 220 w.

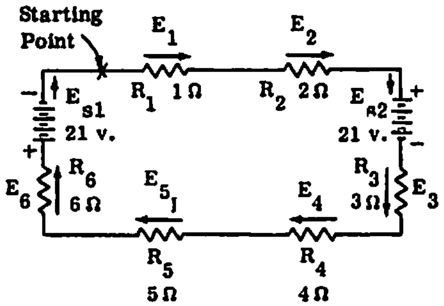


Figure 4-4. Series source with aiding voltage sources

Refer to Figure 4-4 for Frames 40 through 58.

40. So far the source voltage has been given. Let's look at a case in which two voltage sources are used in the same series circuit. Now we have to work out an effective source voltage to use in solving other problems. If the polarities are such that they aid each other (each causes current to flow in the same direction), the sources are simply added and treated as a single source in solving circuit problems. In Figure 4-4, there are two batteries. Examine the circuit carefully. Is the current flow caused by E_{s1} in the same direction as the current flow caused by E_{s2}? ________

- - - - - - - - - - -

yes

41. E_{s1} = ______ E_{s2} = ______

- - - - - - - - - - -

Both values are 21 v.

42. What value of source voltage should you use in solving circuit problems? (Hint: Add E_{s1} and E_{s2}.) ________

- - - - - - - - - - -

42 v. $(E_{s1} + E_{s2} = 21\text{ v.} + 21\text{ v.} = 42\text{ v.})$

43. From Figure 4-4, R_t = _____, I_t = _____.

- - - - - - - - - - -

$R_t = 21\,\Omega$ (Add the six resistances.)

$I_t = 2$ a. $(I_t = \frac{E_s}{R_t} = \frac{42}{21} = 2)$

44. E_4 = ________

- - - - - - - - - - -

8 v. $(E = IR_4 = 2 \times 4 = 8)$

45. E_6 = ________

- - - - - - - - - - -

12 v.

46. E_t = ________

- - - - - - - - - - -

42 v. (2 + 4 + 6 + 8 + 10 + 12 = 42)

47. The power absorbed by R_3 is ________. (Hint: $P = I^2R$.)

- - - - - - - - - - -

12 w.

48. P_t = ________

- - - - - - - - - - -

84 w.

49. In Figure 4-4, the two batteries were aiding. Sometimes when a series circuit has more than one voltage source, they might be connected opposing each other to achieve a specific net voltage. If the voltage sources are connected so that each would cause current to flow in a different direction (as they are in Figure 4-5, on the following page), the voltage sources are opposing. Of course, current in a series circuit cannot flow in two directions at once, so the larger source voltage determines the direction of current flow.

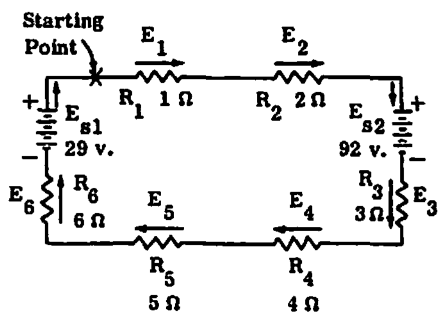


Figure 4-5. Series circuit with opposing voltage sources.

Refer to Figure 4-5 for Frames 49 through 57.

In Figure 4-5, which is the larger voltage source, E_{s1} or E_{s2}? ____

- - - - - - - - - -

E_{s2}

50. In Figure 4-5, current flow is (clockwise/counterclockwise) __________ __________________.

- - - - - - - - - -

clockwise

51. In solving circuit problems involving opposing voltage sources, we have to work out an effective source voltage. To do this, we must trace the circuit to find out the polarity of each voltage source. E_{s1} is (+29/−29) ________ v.

- - - - - - - - - -

−29 (In tracing the circuit, we reach the negative terminal of E_{s1} first.)

52. E_{s2} is (+92/−92) ______ v.

- - - - - - - - - -

+92 v. (We reach the positive terminal first.)

53. The effective source voltage in Figure 4-5 is the algebraic sum of E_{s1} and E_{s2}. The effective source voltage is ________ v.

- - - - - - - - - -

+63 v. (+92 − 29)

54. Once the effective, or net, source voltage is found, circuit problems are solved in the same way as for a single voltage source. We merely regard the effective voltage as the only source voltage. Refer to Figure 4-5 to find the following values.

R_t = ________

I_t = ________

E_5 = ________

- - - - - - - - - - -

$R_t = 21\ \Omega$ (Add all six resistances.)

$I_t = \frac{E_{ff}}{R_t} = \frac{63}{21} = 3$ a.

$E_5 = I_t R_5 = 3 \times 5 = 15$ v.

55. The total of all voltage drops across the six resistors is ______ v.

- - - - - - - - - - -

63

56. $E_{s1} + E_{s2} + E_1 + E_2 + E_3 + E_4 + E_5 + E_6 =$ ________. (Hint: Remember to assign polarities to all voltages.)

- - - - - - - - - - -

zero

57. P_t = ________

- - - - - - - - - - -

189 w. (P = EI = 63 x 3 = 189)

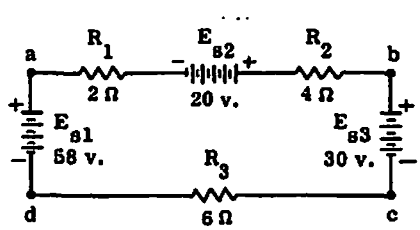


Figure 4-6. Series circuit with three batteries.

Refer to Figure 4-6 for Frames 58 through 61.

58. Even in a more complex problem the principles are the same. In Figure 4-6, the three voltage sources (E_{s1}, E_{s2}, and E_{s3}) are connected so that two are aiding and the third is opposing. Which two voltage sources are aiding? ________________

- - - - - - - - - - -

E_{s1} and E_{s2}

59. What is the direction of current flow? (Hint: Are the combined voltages E_{s1} and E_{s2} larger or smaller than E_{s3}?) ____________________

- - - - - - - - - - -

counterclockwise (E_{s1} and E_{s2} combined are larger than E_{s3}, so they establish the direction of current flow.)

60. What is the effective source voltage? ________

- - - - - - - - - - -

+48 v. (Add algebraically the three source voltages: +58, −30, and +20.)

61. Study Figure 4-6 and answer the following questions.
   (a) What is the current in the circuit? ____________
   (b) What is the voltage drop between point c and point d? ______
   (c) How much power is absorbed by R_2? ________
   (d) What is the total power consumption in the circuit? ________

- - - - - - - - - - -

(a) 4 a. $\left(I_t = \frac{E_s}{R_t} = \frac{48}{12} = 4\right)$

(b) 24 v. $(E = IR = 4 \times 6 = 24)$

(c) 64 w. $(P = I^2R = 4 \times 4 \times 4 = 64)$

(d) 192 w. $(P_t = E_sI_t = 48 \times 4 = 192)$

If you plan to take a break soon, do so now.

Parallel Circuits

62. In a series circuit there is only one path for current flow. As additional loads (such as resistors) are added to the circuit, the total resistance increases and the total current decreases. This is not true in a parallel circuit, as we shall see. In a parallel circuit, each load (or branch) is connected directly across the voltage source. In Figure 4-7, on the next page, the total current flows from the negative terminal of the voltage

source E_s, splits into separate paths at point a, and comes together again at point b.

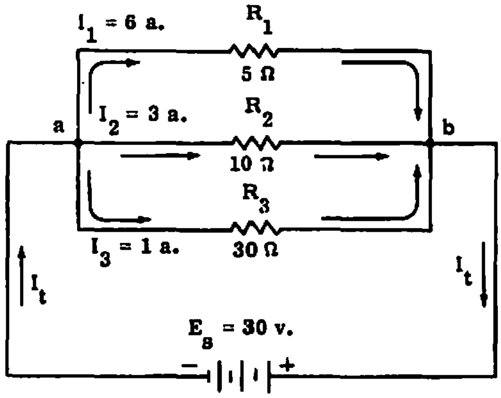


Figure 4-7. Resistors in parallel.

Refer to Figure 4-7 for Frames 62 through 70.

Starting at the negative terminal of the battery in Figure 4-7, how many separate paths for current flow can you trace? __________ (Remember to go along any path only once.)

- - - - - - - - - -

three

63. A parallel circuit is one in which there is (only one/more than one) _____ __________________________ path for current flow.

- - - - - - - - - -

more than one

64. The total current (I_t) is the sum of all the separate currents in the three branches. Later we will learn how to solve for the branch currents. In this case, they are given for simplicity. What is I_t? __________

- - - - - - - - - -

10 a. $(I_1 + I_2 + I_3 = 6 + 3 + 1 = 10)$

65. Examine Figure 4-7. What is the value of E_s? __________

- - - - - - - - - -

30 v.

66. The total resistance (R_t) in this parallel circuit is not the sum of R_1, R_2, and R_3! Since we already know E_s and I_t, we can apply Ohm's Law to find R_t. Use the equation $R = \frac{E}{I}$. R_t = _________.

\- - - - - - - - - -

$$R_t = \frac{E_s}{I_t} = \frac{30}{10} = 3\,\Omega$$

67. You may think it strange that the total circuit resistance is less than that of the smallest resistor. It makes sense, however, if you will consider an analogy with water pressure and water pipes. Let's assume there is some way to keep the water pressure constant. A small pipe offers more resistance to the flow of water than a larger pipe; but if you add another pipe in parallel, even one of very small diameter, the total resistance to water flow is decreased. In an electrical circuit, even a larger resistor in another parallel branch provides an additional path for current flow, so the total resistance is less. (We proved this in Frame 66.) It is probably more accurate to call this total resistance something like "equivalent resistance," but by convention R_t, or total resistance, is used. If we add one more branch to a parallel circuit, the total resistance (increases/decreases) ________________ and the total current (increases/decreases) ________________.

\- - - - - - - - - -

Total resistance decreases; total current increases.

68. The voltage across all branches of a parallel circuit is the same, because all branches are connected directly to the voltage source. Consequently, the current through each branch is independent of the others and depends only on the resistance of that branch, as long as the source voltage remains the same. The currents are already indicated in Figure 4-7. However, you can compute them yourself, since the source voltage (the same for all branches) and the resistance of each branch are both known:

$$I_1 = \frac{E_s}{R_1} = 30 \div 5 = 6 \text{ a.}$$

$$I_2 = \frac{E_s}{R_2} = 30 \div 10 = 3 \text{ a.}$$

I_3 = _____ = _____ = _____ a.

\- - - - - - - - - -

$I_3 = \frac{E_s}{R_3} = 30 \div 30 = 1$ a.

69. The total current, I_t, is the sum of all the currents in the parallel branches. This, in somewhat different words, is Kirchhoff's Current Law, which is discussed later in this chapter. Total current is equal to the sum of the ______________________.

- - - - - - - - - - -

branch currents (or similar wording)

70. You could work out R_t of a parallel circuit by Ohm's Law, but this would be time-consuming, because you would first have to work out each branch current to arrive at I_t. To arrive at the formula for R_t, you must manipulate equations. As you have seen, I_t is the sum of I_1, I_2, and I_3. $I_1 = \frac{E_s}{R_1}$, etc. Here is the equation for total current I_t (the sum of the branch currents) expressed in terms of E and R:

$$\frac{E_s}{R_t} = \frac{E_s}{R_1} + \frac{E_s}{R_2} + \frac{E_s}{R_3}$$

This introduces R_t, the quantity you are trying to determine, into the equation. Since E_s appears as the numerator in all four factors, it is divided out, and the equation then contains only the desired factor R_t:

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$\frac{1}{R_t} = \frac{1}{5} + \frac{1}{10} + \frac{1}{30}$$

$$\frac{1}{R_t} = 0.2 + 0.1 + 0.033$$

$$\frac{1}{R_t} = 0.333 \text{ (approximately)}$$

$$R_t = \frac{1}{0.333}$$

$$R_t = \_\_\_\_$$

- - - - - - - - - - -

3 Ω (Note: It is more convenient to work with decimals rather than fractions. The difference is insignificant.)

71. Note that you must work with <u>reciprocals</u> in solving for R_t in parallel circuits. A reciprocal is an inverted fraction; the reciprocal of the fraction $\frac{4}{5}$, for example, is $\frac{5}{4}$. We consider a whole number to be a fraction with 1 as the denominator, so the reciprocal of a whole number is that number

divided into 1. For example, the reciprocal of R_t is $\frac{1}{R_t}$. What is the reciprocal of 20? ________

- - - - - - - - - -

$\frac{1}{20}$

72. A parallel circuit has three branches whose resistances are 2Ω, 4Ω, and 10Ω. Solve for R_t. (Give your answer in decimals.)

____

- - - - - - - - - -

1.176Ω (1.18) Solution:

$$\frac{1}{R_t} = \frac{1}{2} + \frac{1}{4} + \frac{1}{10}$$
$$\frac{1}{R_t} = 0.5 + 0.25 + 0.10$$
$$\frac{1}{R_t} = 0.85$$
$$R_t = \frac{1}{0.85}$$
$$R_t = 1.176\Omega$$

73. You can see that R_t is always less than the smallest resistance of any branch. A parallel circuit has two branches whose resistances are 1 Ω and 1,000,000Ω. R_t is (less/more) ____________ than 1Ω.

- - - - - - - - - -

less

74. Solving for R_t of a parallel circuit can be sheer drudgery, with many opportunities for arithmetical errors. Fortunately, two shortcuts may be used in certain cases. The first applies only when the parallel resistors (any number of them) all have the same value of resistance. In this case, R_t is found simply by dividing the resistance of one branch by the number of equal branches. Here is the solution for R_t of a parallel circuit that has five branches, each consisting of a 10-ohm resistor:

$$R_t = 10 \div 5 = 2\Omega$$

What is R_t of a parallel circuit that has four branches of 20Ω each?

____

- - - - - - - - - -

5Ω (20 ÷ 4)

75. What is R_t of a parallel circuit consisting of four branches of 16Ω each?

____

- - - - - - - - - -

4Ω

76. The second shortcut may be used when two and only two branches are connected in parallel. This is called the "product over sum" shortcut, because the product of the two resistances is divided by their sum. Here is the solution of R_t when two branches have resistances of 3Ω and 6Ω:

$$R_t = \frac{R_1R_2}{R_1 + R_2} = \frac{3 \times 6}{3 + 6} = \frac{18}{9} = 2\,\Omega$$

Solve for R_t in a parallel circuit where two branches have resistances of 4Ω and 12Ω. R_t = __________

- - - - - - - - - -

3Ω (4 x 12) ÷ (4 +12)

77. Two parallel branches have resistances of 5Ω and 20Ω. R_t = __________.

- - - - - - - - - -

4Ω

Kirchhoff's Current Law Applied to Parallel Circuits

78. Kirchhoff's Current Law states that: At any junction of conductors the algebraic sum of the currents is zero. This is another way of saying that as many electrons leave a junction as enter it. Refer once more to Figure 4-7, appearing in Frame 62. Assume that the current flowing toward junction a (I_t) is positive and the currents flowing away from junction a (I_1, I_2, and I_3) are negative. (You could assume opposite polarities; it is only important that the polarity assigned to current flowing toward a point is opposite to the polarity of any current flowing away from that point.) Kirchhoff's Current Law is then expressed mathematically:

$$+ I_t - I_1 - I_2 - I_3 = 0$$

$$+ 10 - 6 - 3 - 1 = 0$$

I_t in a parallel circuit with three branches is 12 a. The currents in the three branches are 7 a., 3 a., and 2 a. Express mathematically this situation, applying Kirchhoff's Current Law. ____________________

- - - - - - - - - -

$+ 12 - 7 - 3 - 2 = 0$

79. In a three-branch parallel circuit, $I_t = 10$ a., $I_1 = 2$ a., and $I_2 = 3$ a.

What is the value of I_3? ________

- - - - - - - - - - -

$I_3 = 5$ a. Solution: $I_t - I_1 - I_2 - I_3 = 0$

$I_3 = I_t - I_1 - I_2$

$I_3 = 10$ a. $- 2$ a. $- 3$ a.

$I_3 = 5$ a.

80. As in the series circuit, the total power consumed in a parallel circuit is equal to the sum of the power consumed in the individual resistors. All the power equations may be applied exactly as they were in the series circuit. For example, the current through R_1 in Figure 4-7 is 6 a., and the voltage drop across R_1 is 30 v. (Remember that the voltage drop across each branch of a parallel circuit is the same as the source voltage.) Here is the solution for power consumed by R_1, using both $P = EI$ and $P = I^2R$:

(1) $P = EI = 30$ v. x 6 a. = 180 w.

(2) $P = I^2R = 36$ a. x 5Ω = 180 w.

Solve for the power consumed by R_2 using both equations.

(1) $P = EI$ ______________________________

(2) $P = I^2R$ ______________________________

- - - - - - - - - - -

(1) P = 30 v. x 3 a. = 90 w.; (2) P = 9 a. x 10Ω = 90 w.

81. You found that R_t in Figure 4-7 is 3Ω and I_t is 10 a. Solve for P_t using the equation $P = I^2R$. P_t = ________

- - - - - - - - - - -

$P_t = I_t^2R_t = 100$ a. x 3Ω = 300 w.

82. Solve for P_t using the equation $P = EI$. P_t = ________

- - - - - - - - - - -

$P_t = E_sI_t = 30$ v. x 10 a. = 300 w.

83. Problems involving resistance, voltage, current, and power are no more difficult for parallel circuits than for series circuits, although some of the computations take longer. However, it is more difficult to picture the electrical situation in a parallel circuit. If you are given circuit values for a series circuit, you can usually solve any problem associated with that circuit without trouble, simply because there is only one path for current flow. But in solving problems in parallel circuits, you should

always draw a schematic diagram of the circuit, label components, and assign known circuit values. Most people become hopelessly lost without a schematic to help them keep track of known values as well as the unknowns.

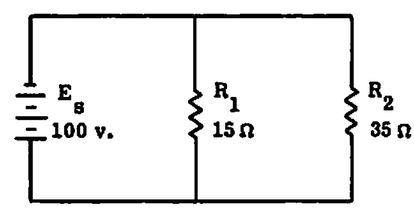
Here is a procedure that will help you to visualize what is known and what you need to do to solve for unknowns:

1. Draw a circuit diagram.
2. Write the given values on the diagram.
3. Write down the values to be found.
4. Write the applicable equations.
5. Substitute the given values and solve for the unknown in each equation.

A circuit consists of a 15-ohm and a 35-ohm resistor connected in parallel across a 100-volt battery. Draw the circuit diagram and label the components. Use a separate sheet of paper.

- - - - - - - - - -

Your circuit diagram should look something like this, although your labeling of components might be different. The physical location of components does not matter as long as the electrical connections are correct.



84. Refer to your diagram for the next few frames. It is helpful to write each new value on the diagram as you solve it. R_t = _________. (Hint: You can use the "product over sum" shortcut.)

- - - - - - - - - -

$R_t = 10.5\Omega$

85. I_t = _________. (Round off your answer to two decimal places.)

- - - - - - - - - -

9.52 a.

86. The current through R_1 = _________

- - - - - - - - - -

6.67 a.

87. The current through R_2 = _________

- - - - - - - - - -

2.86 a.

88. The power consumed by R_1 = _________.

\- - - - - - - - - -

667 w., 666.67 w., or 667.34 w., depending on the power equation you used.

89. The power consumed by R_2 = _________.

\- - - - - - - - - -

286 w. (Some variation, depending on the equation used.)

90. P_t = _________

\- - - - - - - - - -

952 w. (Some variation, depending on the equation used.)

91. Now let's put everything together. Draw your own schematic diagram, using the following information. Three resistors are connected in parallel across a 50-volt battery, labeled E_s for "source voltage." The values of the resistors are:

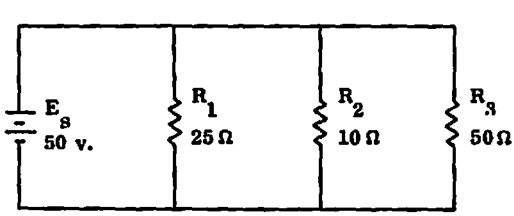
$R_1 = 25\Omega$
$R_2 = 10\Omega$
$R_3 = 50\Omega$

When you have drawn your schematic and have labeled all circuit components with their values, answer the following questions.

1. What is the total resistance (R_t) of the circuit? _________
2. What is the total current (I_t)? _________
3. What are the three branch currents, I_1, I_2, and I_3? _________
4. What is the total power (P_t) consumed by the circuit? ________

\- - - - - - - - - -

Your schematic should look something like this, although the components need not be in the order shown.



1. $R_t = 6.25\Omega$ $\left(\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)$
2. $I_t = 8$ a. $\left(I_t = \frac{E_s}{R_t}\right)$ You could have solved for the branch currents first and then added the three.
3. $I_1 = 2$ a.; $I_2 = 5$ a.; $I_3 = 1$ a. $\left(I = \frac{E_s}{R}\right.$ for each branch.)
4. P = 400 w. ($P_t = E_s I_t$.) You could have found the power of each branch ($P = I^2R$) and then added the three branch powers.

In this chapter you have learned that all the voltage drops in a series circuit must have a total value that is equal to the value of the source voltage although opposite in polarity (Kirchhoff's Law of Voltages). Since there is only one path for current flow, however, the value of current is the same in any part of a series circuit.

In a parallel circuit, the total current splits into the various branch currents, whose sum must equal the total current (Kirchhoff's Current Law). However, the source voltage is impressed across each branch, so all branch voltage drops have the same value as the source voltage.

In other words, current is constant and voltage drops vary in a series circuit, while in a parallel circuit, voltage is constant and current values vary.

You have learned to trace a series circuit to establish the polarities of voltage drops in the circuit, in accordance with Kirchhoff's Law of Voltages.

When a series circuit has more than one voltage source, the voltages either aid or oppose, depending on how they are placed in the circuit, and you must work out a net voltage to represent E_s. (The same principle applies in parallel circuits. We did not deal with multiple voltage sources in those circuits because the solution of such problems is too difficult for this stage of study.)

You have learned that total resistance (R_t) in a parallel circuit requires a special equation (although two shortcuts may be derived from it for certain cases).

Finally, you have learned to solve for values of current, resistance, voltage, and power in both series and parallel circuits.

In this chapter, you have encountered circuits that were purely series or purely parallel. In "real life," of course, circuits usually have portions that are series and other portions that are parallel. We shall examine these circuits in the next chapter.

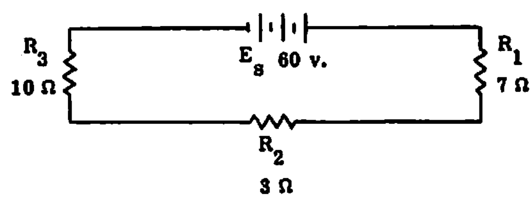
Now, go on to the Self-Test.

Self-Test

These questions will test your understanding of Chapter Four. Write your answers on a separate sheet of paper and check them with the answers provided following the Self-Test.

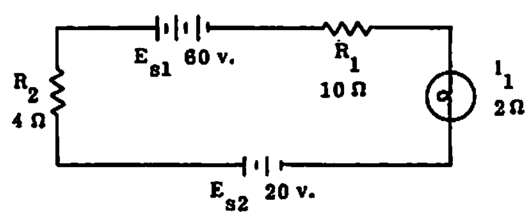
1. What is the difference between a series and a parallel circuit?
2. The sum of all voltage drops in a series circuit is equal to __________.
3. In a series circuit with three resistors, E_s = _____ + _____ + _____.
4. Assuming a series circuit with a battery and two resistors, express Kirchhoff's Law of Voltages mathematically in terms of the circuit voltages.
5. For any total voltage rise in a circuit, there must be an equal total ____.

Refer to the diagram below for questions 6 through 11.



6. Is the direction of current flow clockwise or counterclockwise?
7. Is the voltage drop across R_1 positive or negative?
8. I_t = ?
9. E dropped across R_1 = ?
10. What is the power absorbed by R_2?
11. P_t = ?

Refer to the diagram below for questions 12 through 18.

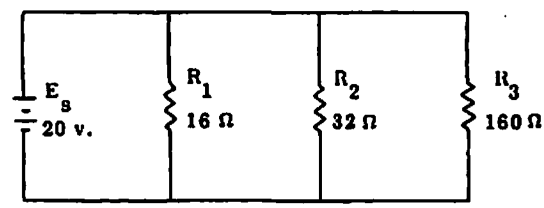


12. Is the direction of current flow clockwise or counterclockwise?
13. What is the effective source voltage?
14. I_t = ?
15. What is the voltage drop across the lamp?
16. What power is consumed by the lamp?
17. What is the current through R_2?

18. P_t = ?

19. As more parallel resistances are added to a circuit, does total resistance increase or decrease?

Refer to the diagram below for questions 20 through 24.



20. R_t = ?

21. I_t = ?

22. How much current flows through R_2?

23. What is the power consumed by R_3?

24. P_t = ?

25. Four 5-ohm resistors are connected in parallel across a battery. What is R_t?

26. Two resistors, whose values are 15 Ω and 30 Ω, are connected in parallel across a battery. What is R_t?

Answers

If your answers to the test questions do not agree with the ones given below, review the frames indicated in parentheses after each answer before you go on to the next chapter. (In many cases there is no one specific reference. In these cases, the appropriate equations are given.)

1. A series circuit has only one path for current flow, while a parallel circuit has more than one path. You might also have mentioned that in a parallel circuit, voltage is constant and current values vary. (1, 80, 109)
2. source voltage (5)
3. $E_s = E_1 + E_2 + E_3$ (6)
4. $E_s - E_1 - E_2 = 0$ (6)
5. voltage drop (7)
6. counterclockwise (22)
7. negative (15)
8. 3 a. $(I = \frac{E}{R})$
9. 21 v. $(E = IR)$

10. 27 w. ($P = I^2R$)

11. 180 w. ($P = EI$)

12. clockwise (49)

13. 40 v. (53)

14. 2.5 a. ($I = \frac{E}{R}$)

15. 5 v. ($E = IR$)

16. 12.5 w. ($P = I^2R$)

17. 2.5 a. (1)

18. 100 w. ($P = EI$)

19. It decreases. (67)

20. $R_t = 10\Omega$ $\left(\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)$

21. $I_t = 2$ a. ($I = \frac{E}{R}$)

22. 0.625 a. ($I = \frac{E}{R}$)

23. 2.5 w. ($P = \frac{E^2}{R}$)

24. 40 w. ($P = EI$; $P = I^2R$; $P = \frac{E^2}{R}$)

25. $R_t = 1\Omega$ (74)

26. $R_t = 10\Omega$ (76)

CHAPTER FIVE

Direct-Current Compound Circuits

In Chapter Four you practiced solving circuit values in series and parallel circuits. However, few circuits in actual use are either pure series or pure parallel circuits; most are a combination of the two. They are called series-parallel, or compound, circuits.

When you finish this chapter you will be able to:

- reduce compound circuits to their simplest form;
- solve for current, voltage, resistance, and power in compound circuits; and,
- solve for currents and voltages in voltage dividers.

Series-Parallel Combinations

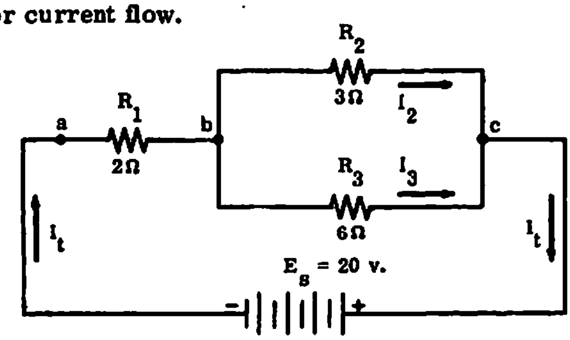
1. At least three resistors are required to form a compound circuit. (Remember that a resistor could be any circuit component across which voltage is dropped—a fuse, a lamp, or some other device.) A one-resistor circuit must be series. A two-resistor circuit could be either series or parallel, but not a combination of the two. Why must a circuit containing only one resistor be a series circuit? ______________________

____

- - - - - - - - - - -

There is only one path for current flow.

Figure 5-1. R_1 in series with parallel combination of R_2 and R_3. Refer to Figure 5-1 for Frames 2 through 16.



2. To better understand a compound circuit, we identify portions of the circuit as either series or parallel. Look at the compound circuit in Figure 5-1. Would the portion of the circuit between points a and b be considered series or parallel? ________________ Why? ________________

____

- - - - - - - - - - -

Series, because the total circuit current flows in that portion of the circuit (or words to that effect).

3. The portion of the circuit between points b and c is parallel because

____.

- - - - - - - - - - -

The total circuit current divides into two separate paths in that portion of the circuit (or words to that effect).

4. Is R_t equal to the sum of R_1, R_2, and R_3 in Figure 5-1? ________ Why or why not? ________________________________

- - - - - - - - - - -

No, R_t is not the sum of the three individual resistances, because the resistance of the R_2/R_3 combination is not the sum of those resistors, since they are in parallel.

5. What is the combined resistance (R_t) of the resistors R_2 and R_3? _____

- - - - - - - - - - -

2Ω (Did you remember to use the "product over sum" shortcut?)

6. What is R_t for the complete circuit in Figure 5-1? _________

- - - - - - - - - - -

$4\,\Omega$ (Add the resistance of R_1, 2Ω, and the combined resistance of R_2 and R_3, 2Ω.)

7. Before you can determine the voltage drop across R_1, what must you solve for? ________________________________

- - - - - - - - - - -

I_t (The total current flows through R_1, because that is the series portion of the circuit. Then you will have the values I and R_1 so you can apply Ohm's Law.)

8. I_t = ________

- - - - - - - - - -

5 a. $(I_t = \frac{E_s}{R_t} = \frac{20 \text{ v.}}{4\Omega} = 5 \text{ a.})$

9. What is the voltage drop across R_1? ________

- - - - - - - - - -

10 v. $(E_{R_1} = I_t R_1 = 5 \text{ a.} \times 2\Omega = 10 \text{ v.})$

10. The branch current I_2 is $3\frac{1}{3}$ a. What is the voltage drop across R_2?

____

- - - - - - - - - -

10 v. $(E_{R_2} = I_2 R_2 = 3\frac{1}{3} \text{ a.} \times 3\Omega = 10 \text{ v.})$

11. The branch current I_3 is $1\frac{2}{3}$ a. What is the voltage drop across R_3?

____

- - - - - - - - - -

10 v. $(E_{R_3} = I_3 R_3)$

12. Now let's see how adding another resistance in parallel changes all the values of voltage and current in the circuit shown in Figure 5-1. If we add another resistor in parallel with R_2 and R_3, the total resistance of the parallel branches will decrease. (R_1 will not change, of course, because it is a fixed value.) Since R_t of the circuit has decreased (R_1 plus a lower value of parallel resistance), I_t must increase, because of the equation $I = \frac{E}{R}$. The increased I_t will cause an increased voltage drop across R_1 because of the equation $E = IR$. To see how this works, we will add a 10-ohm resistor in parallel with R_2 and R_3. For simplicity (and because this is standard practice) we will round off to two decimal places in our calculations.

First find R_t of the parallel branches, which now have resistances of 3Ω, 6Ω, and 10Ω.

$$\frac{1}{R_t} = \frac{1}{3} + \frac{1}{6} + \frac{1}{10}$$

$$\frac{1}{R_t} = 0.33 + 0.17 + 0.10$$

$$\frac{1}{R_t} = 0.6$$

$$R_t = \frac{1}{0.6}$$

$$R_t = 1.67\,\Omega$$

R_t for the whole circuit is now 3.67Ω, since R_1 (2Ω) is added to the parallel resistance of 1.67Ω.

$$I_t = \frac{E_s}{R_t} = \frac{20}{3.67} = 5.45 \text{ a.}$$

The voltage drop across R_1 is found by the equation E = IR, or 5.45 a. x 2Ω = 10.9 v.

By Kirchhoff's Law of Voltages, the voltage drop across the parallel branches is 20 v. − 10.9 v. (the source voltage minus the voltage drop across R_1), or 9.1 v.

Thus, the voltage drop across the parallel portion of a circuit depends on the voltage drops in the series portion, but the voltage drop across each branch of the parallel portion is the same. A parallel portion of the circuit can be regarded as a single resistor whose value is the R_t of all the branches.

When a resistance is added in parallel with a parallel portion of a circuit, does the total resistance (R_t) of that portion increase or decrease?

________________ Why? ______________________________

____

- - - - - - - - - - -

It decreases, because of the equation $\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$
(If you said that it decreases because another path for current flow was provided, you are also correct and probably understand parallel resistance even better.)

13. If the circuit shown in Figure 5-1 is changed as described in Frame 12, does the voltage drop across R_1 increase or decrease? ____________

Why? ____

- - - - - - - - - - -

It increases, because of Kirchhoff's Law of Voltages: $E_s - E_1 - E_2 = 0$. Less voltage is dropped across the parallel resistors, so more is dropped across R_1.

14. The voltage drop across one parallel branch is the same as the voltage drop across all other branches. However, the current through each branch depends on the resistance of that branch. (Remember that resistors are physical devices whose values are fixed.) When the resistance of any branch is changed, or when another branch is added, the current (I_t) flowing in the series portion of the circuit is divided among the branches according to the individual resistance of each branch. I_t flows into the parallel portion, and I_t flows out, in accordance with Kirchhoff's Current Law. Circle the Ohm's Law equation used to find the current of any branch of a parallel circuit.

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

- - - - - - - - - -

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

15. You must keep in mind that all the source voltage in a series circuit must be accounted for in individual voltage drops around the circuit. A parallel portion of a series-parallel circuit can be regarded as a single resistor whose value R_t is the effective resistance of that portion. Can you make a general statement about the voltage drops across the branches of a parallel circuit, or across the parallel portion of a series-parallel circuit?

____

____

- - - - - - - - - -

The voltage drop across any branch of a parallel circuit is the same as the voltage drop across any other branch.

16. You can be sure that branch circuits are truly parallel if they have a common junction at either end. A common junction is either a point at which the total circuit current I_t divides into the branch currents or a point at which the branch currents rejoin to form the total current. One common junction for R_2 and R_3 is point b in Figure 5-1. (Point b is also common to one end of R_1, but we are concerned with the parallel branches.) What is another common junction point? ________________

- - - - - - - - - -

point c

17. Remember that the same difference in potential exists across all branches of a parallel circuit. However, the total current in the series-parallel circuit depends on the effective resistance of the parallel portion and on the other resistances in series with it. Now let's solve some problems in another series-parallel circuit.

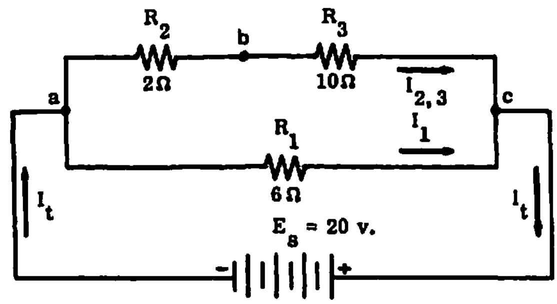


Figure 5-2. R_1 in parallel with the series combination of R_2 and R_3.

Refer to Figure 5-2 for Frames 17 through 22.

Figure 5-2 shows a circuit in which two resistors <u>in series</u> (R_2 and R_3) form one branch of a parallel circuit. The total current I_t flows <u>into</u> the parallel circuit, splitting into two branches at point a. At what point do the branch currents <u>rejoin</u> to form I_t? ________________

- - - - - - - - - -

point c

18. The source voltage E_s (20 v.) is dropped between points a and c. The largest voltage drop is across which resistor? ______ Why? ______

____

- - - - - - - - - -

R_1, because the 20 v. must be divided between R_2 and R_3.

19. The next few frames will show you a systematic way to find the branch currents. What is the resistance of the top branch of the circuit in Figure 5-2? ________

- - - - - - - - - -

12 Ω (Add R_2 and R_3.)

20. R_t = ________

- - - - - - - - - -

4Ω (The "Product over sum" solution is $R_t = \frac{6 \times 12}{6 + 12} = \frac{72}{18} = 4$.)

21. What is the current through the top branch ($I_{2,3}$)? ________

- - - - - - - - - -

1.67 a. $(I = \frac{E}{R} = \frac{20\ v.}{12\Omega} = 1.67$ a.

22. P_t = ________ (You do not need to solve for I_t first.)

\- - - - - - - - - - -

100 w. (Since you already knew E_s and R_t, you should have used the equation $P_t = E_s^2/R_t$.)

Refer to Figure 5-3 for Frames 23 through 27.

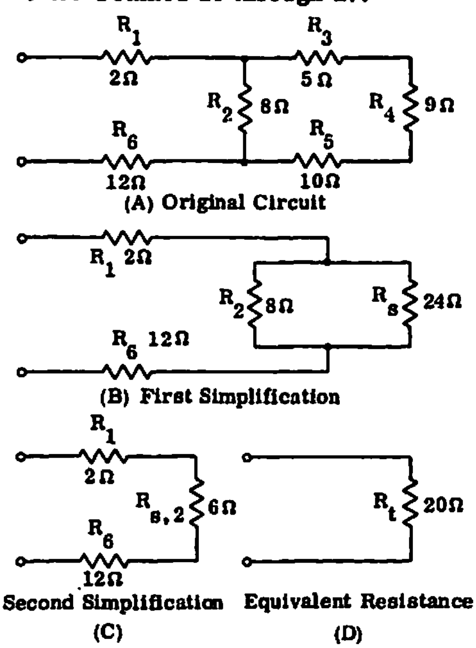


Figure 5-3. Solving total resistance in a compound circuit.

23. Compound circuits may be made up of any number of resistors arranged in numerous series and parallel combinations. Before you can arrive at R_t, the equivalent resistance of the entire circuit, you must first reduce the circuit to its series and parallel equivalents. The original circuit in Figure 5-3 has six resistors. Name the four resistors that make up the parallel portion of the circuit. ____________________

\- - - - - - - - - - -

R_2, R_3, R_4, and R_5

24. The parallel portion of the circuit has how many branches? ________

\- - - - - - - - - - -

two

25. In the original circuit of Figure 5-3, one branch of the parallel portion has a single resistor, R_2, whose resistance is 8Ω. The other branch has three resistors in series. What is their combined resistance? ______

- - - - - - - - - -

24Ω

26. In the first simplification, R_s represents the series equivalent of R_3, R_4, and R_5, which you have just determined. What is the total resistance of the parallel branches only? ________

- - - - - - - - - -

6Ω $\left(R_t = \frac{8 \times 24}{8 + 24} = \frac{192}{32} = 6\right)$

27. In the second simplification, a 6-ohm resistor represents the resistance of the parallel branches. Thus, you are ready to reduce the series-parallel combination to an equivalent resistance, R_t, of ________.

- - - - - - - - - -

20Ω

Refer to Figure 5-4 for Frames 28 through 32.

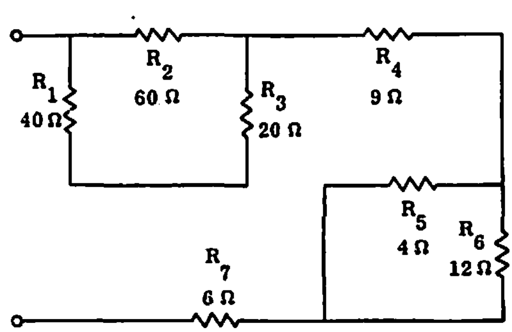


Figure 5-4. Series-parallel combination of resistors.

28. Now let's try a different kind of compound circuit. Figure 5-4 shows a circuit that has parallel portions alternating with single resistors. This circuit is more complicated, so it is important to be sure you can trace through the circuit to identify the series and parallel portions. The

placement of the resistors can be misleading, but you will stay on the right track if you remember exactly what constitutes a parallel portion. Think of the circuit in terms of current flow. The source voltage is not shown, so you have no way of knowing the direction of current flow. However, in this case it doesn't matter. Start at one of the terminals and trace around the circuit. Each time you find a point where the current (if there were a voltage source) would have to split into branches, you know you have one end of a parallel portion of the circuit. (It might help to put a large dot at that point.) When you get to a point where those same branch currents flow together again, you have the other end. Don't be confused by the number of resistors. Any parallel branch could have several resistors in series. You know they are in series if the same current must flow through each. After you have identified all the parallel portions of the circuit, the series portion of the entire circuit includes any resistor through which current flow is the same as the current flow entering the circuit from the voltage source, that is, the total current I_t. In Figure 5-4, name the resistors that make up the series portion of the entire circuit; that is, the resistors that are not found in any parallel branch.

____

- - - - - - - - - -

R_4 and R_7

29. The circuit has two separate parallel combinations. Resistors R_5 and R_6 form one parallel combination. Name the resistors that form the other.

____

- - - - - - - - - -

R_1, R_2, and R_3

30. The equivalent resistance of R_1, R_2, and R_3 is _________.

- - - - - - - - - -

30 Ω

31. The equivalent resistance of R_5 and R_6 is _________.

- - - - - - - - - -

3Ω

32. The total circuit resistance, R_t, is _________.

- - - - - - - - - -

48Ω

Refer to Figure 5-5 for Frames 33 through 51.

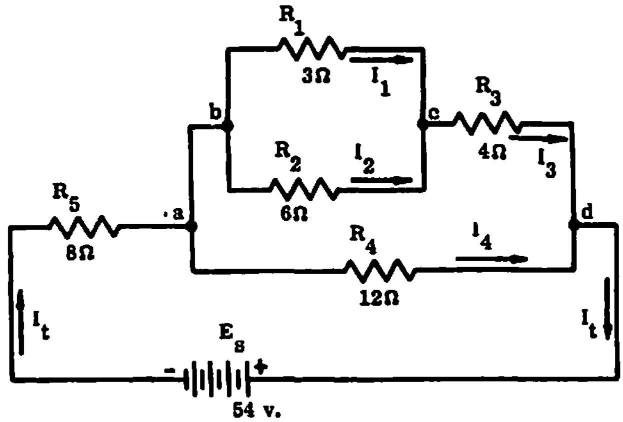


Figure 5-5. A compound circuit.

33. Figure 5-5 shows an even more complicated circuit, because it includes a parallel portion <u>within</u> a larger parallel portion. You have already observed that subscripts are used for labeling both circuit components and their associated values. (However, a number or letter that is a subscript in text might be hand-lettered that way on a schematic diagram.) Any convenient method of labeling may be used as long as it is descriptive. The voltage drop across R_1, for example, could be designated E_{R_1} or E_{bc}. Either correctly identifies the points between which the voltage would be measured. The voltage drop across R_4 could be designated E_{R_4} or __________.

\- - - - - - - - - -

E_{ad}

34. It is often necessary to make intermediate calculations before you can arrive at a specific unknown. For example, before you can solve for I_1, you must first know the voltage drop across R_1 (E_{bc}). Before you can solve for I_t, you must know __________.

\- - - - - - - - - -

R_t

35. Computations can become very confusing unless you keep track of values as you solve them. It is a good idea to write in values on the circuit diagram or to write them on a separate piece of paper. The advantage of writing them on the diagram is that it makes any electrical situation easier to visualize. Before you can find R_t, you must simplify the circuit in successive steps. R_1 and R_2 are parallel branches between points b and c, so their equivalent resistance can be designated R_{bc}. But R_{bc} is part

of one of the parallel branches connected between points _________ and _________.

- - - - - - - - - -

a and d

36. R_{bc} = _____

- - - - - - - - - -

2 Ω

37. R_{bd} includes what three resistors? ____________________

- - - - - - - - - -

R_1, R_2, and R_3

38. R_{bd} = _____

- - - - - - - - - -

6 Ω

39. R_{ad} = ________

- - - - - - - - - -

4 Ω

40. You have now arrived at an equivalent circuit that includes the battery E_s, R_{ad}, and R_5. Does the circuit need to be further simplified? Why?

____

- - - - - - - - - -

No, because it is now an equivalent series circuit.

41. R_t = ________

- - - - - - - - - -

12 Ω

42. By Ohm's Law, the line current (another term for I_t) is ________.

- - - - - - - - - -

4.5 a.

43. The line current flows through R_5, so the voltage drop E_5 is _________.

\- - - - - - - - - -

36 v.

44. According to Kirchhoff's Law of Voltages, the sum of the voltage drops around the circuit is equal to the source voltage. Therefore, E_{ad} is _________.

\- - - - - - - - - -

18 v.

45. I_4 = _________ (Hint: You know E_{ad} and R_4.)

\- - - - - - - - - -

1.5 a.

46. There are only two parallel branches between points a and d. One of these branches, however, includes another pair of parallel branches. You already know that I_t is 4.5 a. and I_4 is 1.5 a. Therefore, the current flowing into the junction at point b is _________.

\- - - - - - - - - -

3 a. ($I_t - I_4$, or 4.5 a. − 1.5 a.)

47. According to Kirchhoff's Current Law, all the current flowing into the junction at point b flows out at point c. I_3 = _________

\- - - - - - - - - -

3 a.

48. E_3 (the voltage drop across R_3) is _________.

\- - - - - - - - - -

12 v.

49. Since E_{ad} is 18 v. and E_3 is 12 v., what is E_{bc}? _________

\- - - - - - - - - -

6 v.

50. I_1 = _________

\- - - - - - - - - -

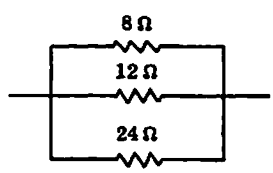
2 a.

51. I_2 = ________

- - - - - - - - - -

1 a. (Note: You could have solved I_2 either by the equation $I_2 = \frac{E_2}{R_2}$ or by $I_2 = I_3 - I_1$.)

52. You have been able to use the "product over sum" shortcut in solving parallel resistance in the last several frames, but remember that you must sometimes use the regular equation, which involves reciprocals: $\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \ldots$ (etc.). Solve R_t in the partial circuit diagram below. R_t = ________



- - - - - - - - - -

4 Ω (Note: If you use fractions, the answer comes out even. If you carry to two decimal places, the answer is 4.03Ω.)

53. Can you think of another way to solve for R_t that avoids reciprocals?

____

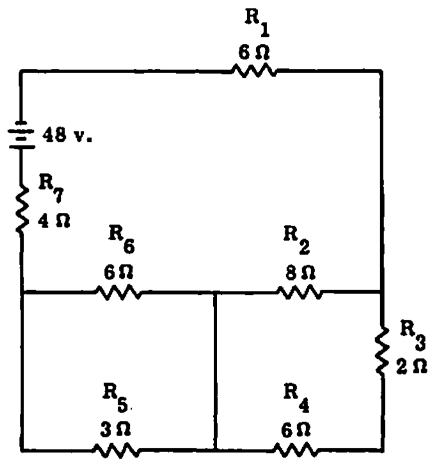
____

- - - - - - - - - -

Perhaps not; but there is a way. You could have solved for the equivalent resistance of two branches using the "product over sum" shortcut. Then you could have repeated the shortcut with that equivalent resistance and the third branch. Try it. Your answer should be the same, 4Ω.

54. As you have learned in this section, any series-parallel circuit can be reduced to an equivalent series circuit. This equivalent circuit is useful to find R_t and I_t, as well as to determine the difference in potential across any parallel portion of a compound circuit. I_t splits into at least two paths when it enters a parallel portion; the voltage drop across that portion (which is the same across all branches) can be used to find each branch current, simply by dividing the branch resistance into the voltage across that branch.

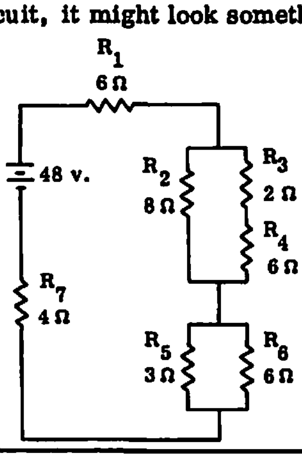
Now let's put it all together by solving some problems in one more compound circuit. The draftsmen who draw schematic diagrams do not like to waste space or lines, so the parallel portions of a circuit are often far from obvious. Such a circuit appears below. It might be helpful to redraw the circuit to make the parallel portions more clear, or to place dots at the end junctions of parallel branches. You are asked to solve for only a few values; however, you will have to find other values before you have enough information to find the specific values requested. If you feel you need more practice, solve for some additional circuit values, such as other voltage drops and branch currents. You can check your own answers, because all values will be consistent (if they are correct) with the values given in the answer to this frame. (For example, the sum of branch currents for each parallel portion must be equal to I_t.)



(a) What is the voltage drop across R_1?
(b) What is the voltage drop across R_4?
(c) What is the current through R_6?

- - - - - - - - - - -

If you redrew the circuit, it might look something like this:



(a) The voltage drop across R_1 is 18 v.

1. Find R_t of each parallel portion: R_t of R_2, R_3, and R_4 is 4Ω; R_t of R_5 and R_6 is 2Ω. R_t of entire circuit is 16Ω (6Ω + 4Ω + 2Ω + 4Ω).
2. $I_t = \frac{E_s}{R_t} = \frac{48 \text{ v.}}{16\,\Omega} = 3 \text{ a.}$
3. $E_{R_1} = I_t R_1 = 3 \text{ a.} \times 6\,\Omega = 18 \text{ v.}$

(b) The voltage drop across R_4 is 9 v.

1. First find the voltage drop across this parallel portion. $E = I_t R = 3 \text{ a.} \times 4\Omega = 12 \text{ v.}$
2. Find current through R_4. $I_{R_4} = \frac{12 \text{ v.}}{8\Omega} = 1.5 \text{ a.}$
3. $E_{R_4} = 1.5 \text{ a.} \times 6\Omega = 9 \text{ v.}$

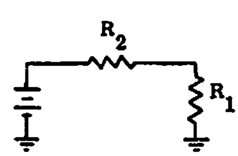
(c) The current through R_6 is 1 a.

1. Find the voltage drop across this parallel portion. $E = I_t R = 3 \text{ a.} \times 2\Omega = 6 \text{ v.}$
2. $I_{R_6} = \frac{E}{R_6} = \frac{6 \text{ v.}}{6\,\Omega} = 1 \text{ a.}$

Voltage Dividers

55. In practically all electronic devices, such as radio receivers and transmitters, certain design requirements (which require different voltages) recur many times. It is both impractical and unnecessary to have a separate power supply for each voltage requirement, because the same result can be achieved by voltage dividers.

To understand the discussion that follows, you need to know a few new terms and a new symbol. A ground is merely a common connection point—usually the metal chassis of the equipment. For example, several wires might be connected to the sheet metal frame of a radio. All such connection points are electrically the same, so each point in the schematic could be represented by the "ground" symbol. If one side of the power supply is connected to ground, every point connected to ground is also electrically connected to that side of the power supply. Normally the grounded side is negative. In the diagram below, the negative side of the battery and R_1 are both grounded.



Draw the symbol for "ground."

- - - - - - - - - - -

 (Note: The number of horizontal lines is not important, but each line is shorter than the one above it. The lowest line could be a dot.)

56. Many devices draw very small amounts of current. To reduce the current to the value required, large values of resistance must be used. Two common prefixes in electricity are "milli-," which means 1/1000th (or 0.001) and "kilo-," which means 1,000. One milliampere is written "1 ma." One kilohm is usually abbreviated 1 kΩ or simply 1 K. (Don't be confused by the interchangeability of small and capital letters in some abbreviations; conventions differ somewhat.)

(a) If the source voltage is 100 v. and the total circuit resistance is 50 K, the current is 0.002 a., or __________ ma.

(b) If the source voltage is 40 v. and the total circuit resistance is 10 K, the current is __________ ma.

(c) The value 6 ma. is the same as __________ a.

(d) 50 K is the same as __________ Ω.

- - - - - - - - - - -

(a) 2; (b) 4; (c) 0.006; (d) 50,000. 50 K could also be written 50 kΩ. (Note: For help in working with very large numbers and small decimals, you may wish to review the laws of exponents in Appendix III, page 278.)

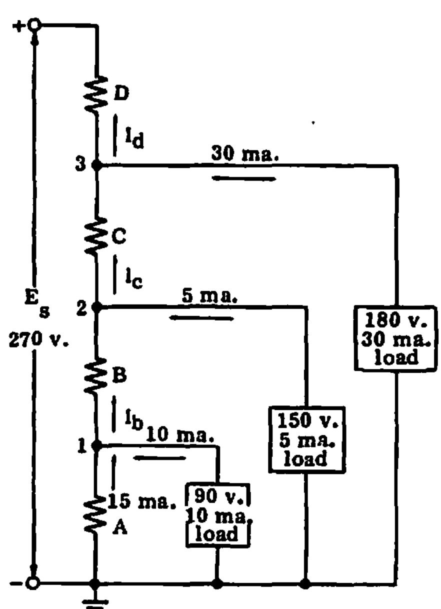


Figure 5-6. Voltage divider, to solve for R and P.

Refer to Figure 5-6 for Frames 57 through 66.

57. A typical voltage divider consists of two or more resistors connected in series across the primary power supply. The primary voltage E_s must be as high as or higher than any of the individual voltages it is to supply. As the primary voltage is dropped by successive steps through the series resistors, any desired fraction of the original voltage may be "tapped off" to supply individual requirements. The value of each series resistor used is determined by the voltage to be dropped across it. In Figure 5-6, a voltage divider is connected across a 270-volt source E_s. (The voltage source is often indicated on schematics by showing only the terminals.) The voltage divider in Figure 5-6 consists of four resistors, labeled A, B, C, and D. The points (1, 2, and 3) at which partial voltages are tapped off are called "taps." In this case, external loads are connected to all three taps, and the voltage and current requirements of each load are indicated on the schematic. The load placed across resistor A is 90 v. and 10 ma. The voltage drop across A, measured between ground and tap 1,

is __________ v.

\- - - - - - - - - -

90

58. The Ohm's Law equations have so far been based on the basic units: ohms, amperes, and volts. But now we are starting to use milliamperes (called "milliamps") and kilohms. These should cause no problem as long as you are careful to use the appropriate decimals for milliamperes and the correct number of zeroes for kilohms. But since these two units of measurement are quite common, you should know a short cut. Since E = IR, you know that 1 a. flowing through a 1-ohm resistor drops 1 v. A current of

1 ma. flowing through a 1-kilohm resistor drops __________ v.

\- - - - - - - - - -

1 (E = 0.001 x 1,000 = 1)

59. Thus, in an equation where all resistances are in kilohms and all currents are in milliamperes, voltage is in ____________________.

\- - - - - - - - - -

volts

60. According to Kirchhoff's Law of Currents, the current flowing through resistor B must be the sum of the current flowing through A and that flowing through the load across A. I_b is __________.

\- - - - - - - - - -

25 ma.

61. The required voltage for the 150-volt load is obtained by selecting a tap on the voltage divider at which the potential difference (between the tap and ground) is 150 v. The combined voltage drop across resistor A and resistor B is also 150 v. Why? ______________________________

____

- - - - - - - - - -

Because the voltage drop across all parallel branches is the same.

62. The current I_c is 30 ma. How do we know? ____________________

____

- - - - - - - - - -

The load current of 5 ma. is added to current I_b, which we know is 25 ma.

63. What is current I_d? __________

- - - - - - - - - -

60 ma. (I_c plus the load current of 30 ma.)

64. I_t in Figure 5-6 flows through only one resistor of the voltage divider. Which one? __________

- - - - - - - - - -

D. (This resistor is not part of any parallel portion of the circuit. It is in series with the voltage source.)

65. The correct voltage requirements are supplied to the three loads in Figure 5-6 because of the varying differences in potential at taps 1, 2, and 3. These differences in potential are with respect to ground. For example, the voltage drop across resistor A is 90 v. This is also the difference in potential between tap 1 and ground. The voltage drop across resistor B is 60 volts. The difference in potential, with respect to ground, between tap 2 and ground is 150 v. Thus, the two voltage drops of 90 v. and 60 v. represent a difference in potential of 150 v. The voltage drop across resistor C (between taps 2 and 3) is 30 v. What is the difference in potential between tap 3 and ground? __________

- - - - - - - - - -

180 v.

66. We now know all the values of voltage and current necessary to find the values of resistance in the circuit. For example, we can find the value of resistor A because we know the current through it and the voltage dropped across it.

(a) R_A = ________

(b) R_B = ________ (Hint: First find E_B. You already know E_A and E_{A+B}.)

(c) R_C = ________

(d) R_D = ________

- - - - - - - - - - -

(a) 6 K $\left(R_A = \frac{E_A}{I_A} = \frac{90 \text{ v.}}{15 \text{ a.}} = 6 \text{ K}\right)$

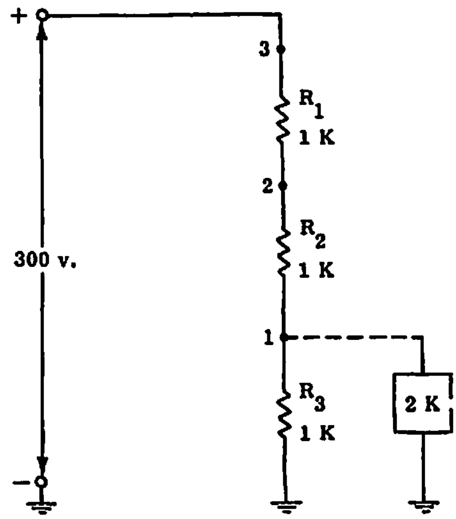
(b) 2.4 K (E_B = 150 v. − 90 v. = 60 v.)

(c) 1 K (E_C = 180 v. − 150 v. = 30 v.)

(d) 1.5 K

67. We have seen, in working the problems associated with Figure 5-6, that the voltage divider is an excellent application of the properties of parallel circuits. Each external device, or "load," connected to one of the taps on the voltage divider is a branch in parallel with part of the voltage divider. As we move to a tap farther away from ground, which is the negative end of the voltage source in Figure 5-6, we select a larger difference in potential between that tap and ground. Since all branches of a parallel circuit "see" the same difference in potential, we can select a voltage appropriate to the external load. Remember that adding another resistance in parallel with part of the circuit will decrease the resistance of that part of the circuit. This will in turn decrease the difference in potential across the parallel circuit. Thus, the voltage across the parallel circuit is lower, but the voltage across the series resistors is correspondingly greater. This is consistent with Kirchhoff's Law of Voltages. It makes sense, because the total current flowing in the circuit has also increased (since the total resistance is lower).

The circuit shown on the following page shows a voltage divider consisting of three one-kilohm resistors connected to a 300-volt source. Before the load is connected, the total circuit current is 100 ma. (0.1 a.) and each resistor sees a voltage drop of 100 v. The dashed line indicates that the two-kilohm load has not been connected to the tap.



After the load is connected:

(a) What is the difference in potential between tap 3 and ground?

____

(b) What is the resistance between tap 1 and ground? __________

(c) What is the current through R_2? __________

(d) What is the difference in potential between tap 1 and ground?

____

(e) What is the current through the two-kilohm load? __________

- - - - - - - - - -

(a) 300 v. (Same as the source voltage.)
(b) 0.67 K (Use the "product over sum" method.)
(c) 112.36 ma. (E_s divided by R_t, or 300 v. ÷ 2.67 K. This is I_t.)
(d) 75.28 v. (I_t times 0.67 K)
(e) 37.64 ma. (75.28 v. ÷ 2 K)

68. Now let's see how currents are distributed when external loads are connected to a voltage divider. In Figure 5-7, on the following page, resistances are given for R_4, R_5, R_6, and R_7 (the voltage divider), but not for the three loads, R_1, R_2, and R_3. The source voltage is known (E_s = 510 v.), and enough information about currents is given to enable us to work out all the voltage drops in the circuit; but the only way to go about it is to apply Kirchhoff's Law of Currents.

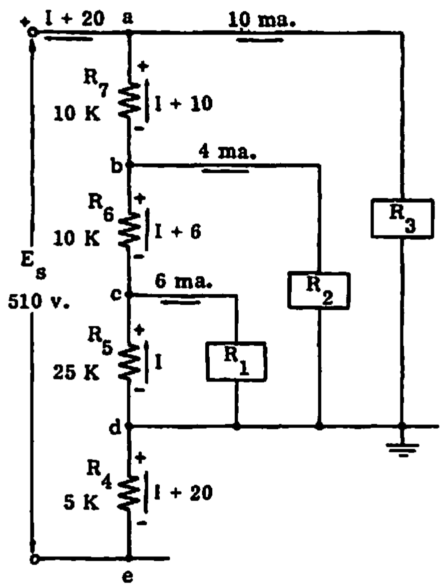


Figure 5-7. Voltage divider, to solve for E and R.

Refer to Figure 5-7 for Frames 68 through 82.

The only resistor through which <u>all</u> circuit current flows is ________.

- - - - - - - - - -

R_4

69. The load currents, as shown in the diagram, are 6 ma., 4 ma., and 10 ma. The only resistor through which <u>no</u> external load current flows is ______.

- - - - - - - - - -

R_5

70. Thus, if we first solve for I (the current through R_5), we can easily find the current through the other resistors of the voltage divider (R_6 and R_7). The current through R_6 is I plus 6 ma. (the current through R_1); and the current through R_7 is I plus 6 ma. plus 4 ma. (the current through R_2). Naturally, once we know both the current and the resistance for any resistor, we can find the voltage drop across that resistor. We shall also know the voltage across each external load. Why? ________________

____

- - - - - - - - - -

Each load is in parallel with a portion of the circuit for which the voltage drop can be found, and we know that voltage drops across parallel branches are equal.

71. To find I, the current through R_5—since we don't know the voltage drop across R_5—we must set up an equation that expresses all voltage drops in terms of current and resistance (E = IR). Start with your knowledge that all voltage drops in the circuit must equal E_s:

$$E_4 + E_5 + E_6 + E_7 = E_s$$

You know that the current through R_5 (I) and all load currents (20 ma. in all) flow through R_4. You can express E_4, then, in terms of current and resistance: $E_4 = 5(I + 20)$. I is the current that does not flow in the loads, and 20 ma. represents the total load current. The resistance of R_4 is 5 K. You are working with milliamperes and kilohms, so the resistance is simply 5 in the equation. Complete the equation that will express all voltage drops, expressing each voltage drop in terms of R and I.

$$5(I + 20) + 25I + \_\_\_\_\_ + \_\_\_\_\_ = 510$$

- - - - - - - - - - -

$5(I + 20) + 25I + 10(I + 6) + 10(I + 10) = 510$

72. Now collect your terms, and your equation is simplified as:

$$5I + 100 + 25I + 10I + 60 + 10I + 100 = 510$$

$$50I + 260 = 510$$

$$50I = 250$$

$$I = \_\_\_\_\_$$

- - - - - - - - - - -

5 ma.

73. The current through R_5 is ________.

- - - - - - - - - - -

5 ma.

74. The current through R_4 is ________.

- - - - - - - - - - -

25 ma.

75. E_4 = ________

- - - - - - - - - - -

125 v.

76. E_5 = ________

\- - - - - - - - - - -

125 v.

77. What is the voltage drop across R_1? ________

\- - - - - - - - - - -

125 v. (R_1 is in parallel with R_5.)

78. What is the resistance of R_1? ________

\- - - - - - - - - - -

20.83 K

79. What is the voltage across R_2? (Hint: First you have to find E_6.) ____

\- - - - - - - - - - -

235 v. (E_5 + E_6, or 125 v. + 110 v., since R_2 is in parallel with R_5 and R_6.)

80. How much power is absorbed by R_3? ________

\- - - - - - - - - - -

3.85 w. (The voltage drop across R_3 is $E_5 + E_6 + E_7$, or 385 v. $P = EI = 385 \times 0.01 = 3.85$.)

81. How much power is absorbed by R_2? ________

\- - - - - - - - - - -

0.94 w.

82. P_t = ________

\- - - - - - - - - - -

12.75 w. ($P_t = E_s I_t$ = 510 v. x 25 ma. = 12.75 w.)

The circuits described in this chapter are the kind most frequently encountered in actual practice; that is, they have both series and parallel elements. It is necessary to look at the circuit as a whole to find some of the values. For example, you need to know I_t before you can solve for the voltage across parallel branches—and this voltage is needed to solve for the current through a specific branch.

You must approach the direct-current compound circuit systematically, first identifying the parallel portions and then reducing the entire circuit to its simplest form: an equivalent series circuit. Once you have done this, it is not difficult to solve any problem of current, voltage, resistance, or power.

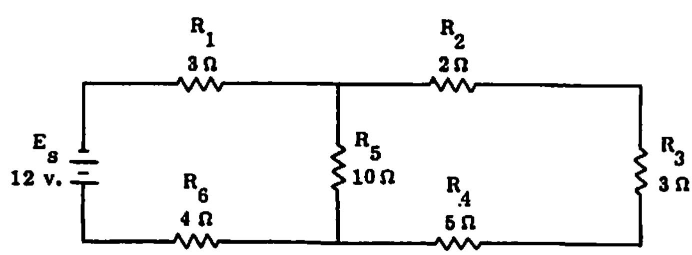
The voltage divider is merely one application of a compound circuit. Each external load tapped into the voltage divider is merely a branch of a parallel circuit. However, its resistance changes the equivalent resistance of one portion of the circuit, and thus, the values of voltage and current throughout the circuit.

If you feel you understand the basic concepts of the compound circuit and the voltage divider, go on to the Self-Test.

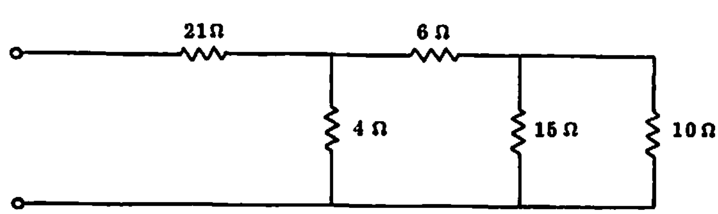
Self-Test

These questions will test your understanding of Chapter Five. Write your answers on a separate sheet of paper and check them with the answers provided following the Self-Test.

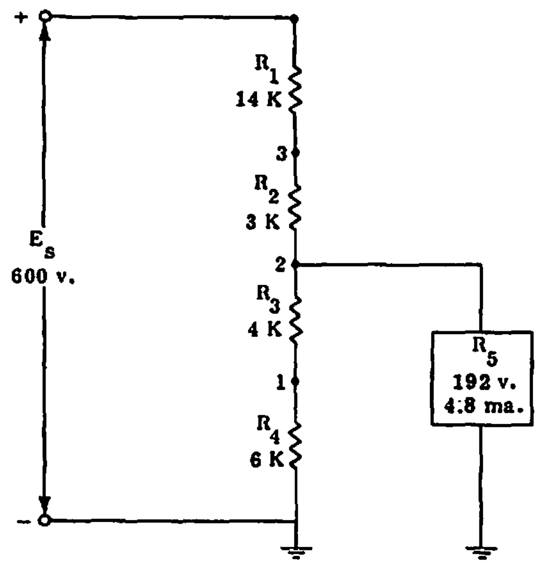
Refer to the diagram below for questions 1 through 4.



1. What is the total resistance R_t of the circuit?
2. What is the total current I_t in the circuit?
3. What is the voltage across R_3?
4. What is the total power consumed in the circuit?
5. What is R_t, the equivalent resistance, of the circuit below?



6. Refer to the diagram below.



(a) What is the current through R_1?
(b) What is the voltage across R_4?
(c) What is the difference in potential between tap 3 and ground?
(d) How much current would flow in the circuit if R_5 were disconnected?

Answers

If your answers to the test questions do not agree with the ones given below, review the frames indicated in parentheses after each answer before you go on to the next chapter. (Where there is no one specific reference, the appropriate equation is given.)

1. 12Ω (6)
2. 1 a. (8)
3. 1.5 v. (17–21)
4. 12 w. (22)
5. 24Ω (23–27)
6. (a) 24 ma. (67)
   (b) 115.2 v. (67)
   (c) 264 v. (67)
   (d) 22.22 ma. $\left(I_t = \frac{E_s}{R_t}\right)$

Fast Copy and the UofA BookStores encourage you to recycle your Class Notes!

Bring these notes to Fast Copy
(located in the Student Union Memorial Center)
at the end of the semester
and we will Recycle them!

Save Natural Resources, Reduce Waste, Protect the Environment!

NO RETURNS, REFUNDS, OR EXCHANGES ON CLASS NOTE PACKETS