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Residential Wiring

to the 2011 *NEC*®

by Jeff Markell

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INTRODUCTION

This book was written for anyone who intends to make a living wiring residential buildings. If you can understand and follow the instructions in this manual, you should have no trouble installing safe, modern, efficient electrical systems in homes and apartments.

As an electrician, you need to know how to use a wide variety of tools and materials. This manual describes the tools that should be in every electrician's tool box, and suggests how they can be used to best advantage. I'll also explain what you should know about electrical materials: wire, cable, conduit, fixtures, boxes, switches, breakers and panels. There's a correct tool and a right material for every purpose. Sometimes selecting the right tools and materials isn't easy. After reading this book, you should have little trouble choosing both the tools and materials appropriate for the work you do.

This manual isn't a book of electrical theory. But every professional electrician needs some background on how electricity is generated and distributed. And, of course, you should know how Ohm's Law and Watt's Law are used to design electrical systems. The first two chapters cover these important subjects.

If you've worked as an electrician for some time, you know that nearly everything an electrician does is governed by the *National Electrical Code®*, also referred to as *NFPA 70®*, published by the *National Fire Protection Association® (NFPA®)*, and the International Code Council (ICC) Electrical Code. For our purposes, the only right way is the code way. Until you're comfortable with the *NEC®*, doing everything the code way can be a nuisance. Once you understand the code and the reasons for code requirements, you may have a different perspective. Experienced electricians agree that the *NEC* protects everyone (including electricians and electrical contractors) and is a good guide to professional practice and should be followed — even if the building inspector didn't spot a problem or enforce it.

And here's yet another reason to strictly adhere to the code. If ever there's a problem with the wiring in a building, such as an electrical fire, as long as you've done the installation to code, you're probably off the hook. But if they find you haven't, they're going to hang you on it.

This book will help you follow the code, but it isn't a substitute for the *NEC*. Every professional electrician needs a copy of the current code used in the jurisdiction where they're working. Many bookstores sell the *NEC*, or you can order a copy from this publisher, using the order form bound into the back of this book, or from their website: www.craftsman-book.com.

But just having the current *NEC* isn't enough. Many cities and counties don't adopt the model *NEC* exactly as published, nor should you assume every jurisdiction is using the newest code. Each jurisdiction has its own way of reviewing the code updates and approving them, with or without local practices and amendments. When the changes from one generation of code to the next code are insignificant, some jurisdictions choose to keep the old code and wait for the next revision.

Once you have the *NEC* that's adopted in the jurisdiction where you're working, ask at the local building department about amendments or changes that apply in that jurisdiction. Keep those changes with your copy of the *NEC*. Sometimes employing a local licensed electrician to work on a residence that's not in your usual jurisdiction is an option. Always keep in mind that you're responsible for the hazards you encounter or produce while working on an electrical system.

In this book I'll explain floor plans, cable plans and wiring diagrams in detail. This is important information for every electrician. The code has a lot to say about types of outlets, spacing of outlets, what must be switch-controlled and what need not be switch-controlled. The work you do will have to follow the plans and comply with the code. The information in this book should help you understand and follow plans prepared for your jobs. However, the diagrams I've included and the associated text are meant to assist you with general knowledge, troubleshooting and advice in solving residential electrical problems. They aren't designed for you to rely on unquestionably. They may be incomplete or contain jurisdictional errors and may not always apply exactly to your specific problem. They are strictly teaching examples, and not intended for your direct use or for nonresidential electrical systems or systems outside the United States.

Finally, I'll explain how to diagram the circuits you're likely to find in a home or apartment. As a teacher of electrical wiring for many years, I've found that a student who can diagram a circuit correctly has a reasonably good chance of wiring it correctly as well. And a student who can't diagram a circuit probably can't install it either!

Now let's get down to business — what you need to know to wire homes and apartments.

Jeff Markell

1

ELECTRICAL ENERGY

In order for electricians to understand their work sufficiently and keep current in the field, they need a good background in electricity and its capabilities. But they also need to know some basics about the nature of matter, since the creation and transfer of electrical energy is primarily a function of the properties of matter at the molecular level. Electricity has always been, and typically still is, mysterious. It's an invisible form of energy, but as you've probably discovered, it can make its presence extremely evident. This is a practical book on how electrical wiring in a small building should be done to meet accepted standards of good workmanship, and to comply with the provisions of the *National Electrical Code (NEC)*. It doesn't focus on theory, so the discussion of theoretical matters will be minimized.

Historical Introduction

It might be surprising that, as far back as 600 BC, the Greeks amazed themselves with elementary uses of static electricity. For example, they discovered that a piece of amber rubbed with cloth attracted bits of straw, hair, etc. Their word for amber was "elektron," which is the root of "electron," "electricity," "electronics," and other words containing "electro."

"The ancients" also discovered that certain heavy black stones they occasionally found mysteriously attracted iron. Since these stones were often found in a part of Asia Minor called Magnesia, they were called magnets. Naturally, all manner of hocus pocus was created to explain these curious phenomena — none of them with much semblance to the facts as we now know them.

Over many centuries, observations indicated that various other materials had characteristics similar to amber. These materials could also be rubbed to attract light objects. Scientists developed a theory that the rubbed materials would leak a "fluid-like substance" that caused the attraction. This fluid was called *electricity*. Theorists of the early 18th century, discontent with just one "fluid," hypothesized that there were two fluids. One was called "vitreous" and the other was "resinous." The difference was based on the nature of the substance being rubbed. By the middle of the 18th century, Ben Franklin went back to the "one fluid" theory. He decided that the two fluids were simply different aspects of the same thing. When an object had too much of this electric fluid it was "positive," if it had too little it was "negative," and if it was neither, it was "neutral." While those in scientific fields were dissatisfied with this theory, it was the only one available until the early 20th century. At that later time, investigating the structure of matter produced a more satisfactory alternative.

The Composition of Matter

Matter is anything that has mass and occupies space. It exists in the following three states:

1. Solid — such as rock
2. Liquid — such as water
3. Gaseous — such as the air around us

With variations in temperature and pressure, matter can be changed from one state to another. Remove enough heat from a quantity of water by reducing the temperature, and at 32 degrees F, it'll change from a liquid to a solid — ice. Add enough heat to the same quantity of water by increasing the temperature, and at 212 degrees F it'll start to vaporize, changing from a liquid to a gas.

Although a particular type of matter may change state from solid to liquid to gaseous, the component building blocks it's made of remain the same. So, "What's matter made of?" To find out, we must divide, subdivide and subdivide again to reach the smallest particle that maintains the characteristics of that type of matter, such as water, steel, or foam plastic. The smallest particle that maintains the characteristic of the material is a "molecule." Each kind of matter has a corresponding different molecule. But the molecule definitely isn't the smallest part.

Molecules are composed of even smaller parts called "atoms." Water, for example, is composed of molecules made of two hydrogen atoms plus one oxygen atom — H_2O. All matter, then, consists of the atoms of some 118 elements combined in different compounds to form the molecules that distinguish different substances from each other. We will discuss how atoms accomplish combining into molecules after we look more closely at the atom itself.

The atoms that compose molecules are quite complicated structures. Each one seems to be a miniature solar system, consisting of a nucleus surrounded by varying numbers of revolving electrons. The nucleus contains various particles, such as protons, neutrons, positrons, neutrinos, mesons, and even a few odd bits called "quarks" and "charms." We're primarily concerned with the bulk of the nucleus consisting of the protons and neutrons. The number of protons in the nucleus differentiates the atoms of the 118 elements from each other. The number of protons in the atom's nucleus is its "atomic number," for example hydrogen is #1, helium is #2, and so on.

Protons are positively charged, neutrons have no electrical charge, and the orbiting electrons are negatively charged. Since, under normal conditions, atoms are electrically neutral, an atom of any element will contain equal numbers of electrons and protons. The number of neutrons, along with the various other nuclear components (neutrinos, mesons, etc.), has nothing to do with the electron-proton balance. Hydrogen has no neutrons, while the 92 protons of uranium are outnumbered by 146 neutrons.

While the magnitude of the opposite electrical charges in electrons and protons is equal to each other, the difference in mass between the two is staggering. The mass of a proton is 1,840 times that of an electron. There's a similarity between what's observed on a huge scale in the solar system to the minute scale in the atom. All but a tiny part of the solar system's mass is contained in the sun. Similarly, all but a tiny part of an atom's mass is contained in the nucleus.

The solar system's planets are held in their orbits around the sun by complex factors involving the mutual attraction of their gravitational fields with the sun's, and their masses and velocities. Electrons are held in their orbit around the nucleus by the electrostatic attraction between their negative charges and the proton's positive charges in the nucleus, including a relationship between mass and velocity.

At this point, the parallel between the atom and the solar system breaks down. Each planet of the solar system differs greatly from the other in mass, composition, orbital velocity, and other characteristics. However, the electrons orbiting the nucleus of an atom do not differ.

The electron must maintain a constant speed to sustain the centrifugal force that keeps it from falling into its nucleus or spinning away from its nucleus. Because of its mass, it must also have a level of energy

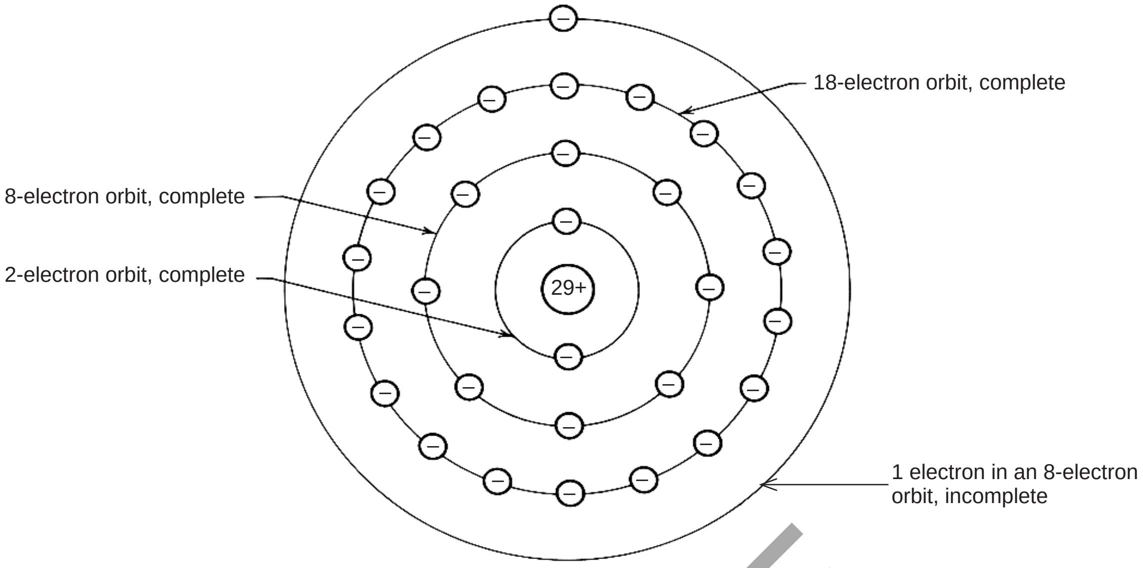

Figure 1-1
Diagram of an atom

resulting from a combination of its mass and velocity. Only a very limited number of specific energy levels are possible for electrons; there are seven altogether. As an electron can only occupy an orbital path suitable to its energy level, there are seven possible orbits.

The more complex atoms might have as many as 100 electrons, but since only seven possible energy levels exist, the electrons must group at various appropriate orbit distances from the nucleus, forming "shells" in layers around it. See Figure 1-1. A consistently repeated pattern is found in the formation of these shells. The innermost shell (#1) can hold no more than two electrons. Any number above two starts the second shell, which holds up to eight. When it's filled, the third shell is started.

At this point, the picture becomes a little more complicated. The third shell (#3) holds up to 18 electrons; however, the *outermost* shell of any atom, regardless of which one, can't hold more than eight. So, when shell #3 is on the outside, with eight electrons, the next electron must orbit in shell #4. Only after shell #4 has one or two occupants can the rest of the 18 possible spaces in #3 be filled. When shell #4 has eight electrons, shell #3 will already have its allotted 18. When #4 is the outermost shell, holding eight electrons, then shell #5 starts. Shell #4 can hold 32 electrons. When it has 32, and shell #5 is up to eight, shell #6 is started. Once shell #6 is completed and shell #7, the last possible electron shell is started in a similar way. With all elements, it's the spare electrons of the outer shell — whatever shell number that is — that take part in any of the various chemical and electrical phenomena. These are called "valence electrons."

Formation of Molecules

Regardless of its shell number, the outermost shell of any atom can't contain more than eight valence electrons. Any atom that has all eight is stable, and doesn't normally combine with other atoms. The atoms with valence electrons anywhere between one and seven, trying to attain stability, are available to combine with other atoms to form molecules. The process of molecule formation is called atomic bonding. This process occurs in any one of the following three ways:

1. Ionic bonding
2. Covalent bonding
3. Metallic bonding

Ionic Bonding

An atom alone will contain matching numbers of electrons and protons, which, since they have opposite electrical charges, results in a neutral charge for the atom as a whole. However, this matter of valence electrons gets in the way. An atom with more than four but fewer than eight valence electrons is unstable. It tries to obtain whatever number of valence electrons is missing to fill its outer shell to eight. In contrast, an atom with fewer than four valence electrons is also unstable, but willing to unload its excess.

Where an atom with one valence electron meets another one with seven, there's a tendency for the one to join the seven, stabilizing both atoms. However, in the process, something else happens. The atom that lost an electron now has a net *positive* electrical charge of one. The atom that picked up an electron has a net *negative* electrical charge of one. An atom that's no longer electrically neutral but has a net positive or negative charge has become an "ion." Ions with opposite electrical charges are attracted to each other, tending to combine via "ionic bonding" to form molecules.

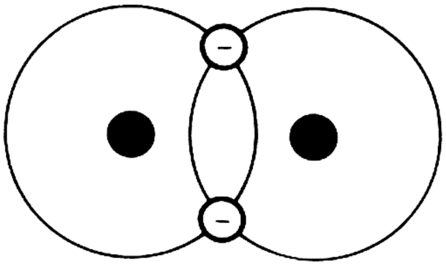

Figure 1-2
Covalent bond of two hydrogen atoms

Covalent Bonding

Hydrogen with the atomic number "1" has only a single electron in the #1 shell. It's unstable because that shell is incomplete without two electrons. One way it stabilizes is to join with another hydrogen atom to form a hydrogen molecule in which the two component atoms share their two electrons. See Figure 1-2. This is an example of "covalent bonding."

Metallic Bonding

Copper is a good example of "metallic bonding" because it's the most commonly-used material for electrical wires. The atom in this case has 29 electrons. Shell #1 is complete with two, shell #2 is complete with eight, and shell #3 is filled with the next 18. That totals 28. The 29th is a lone valence electron in shell #4, which is loosely held and has a tendency to wander off, becoming a "free electron." The copper atom has become a positive ion, and so have a lot of other atoms that have also lost their single valence electrons. Although like charges repel, the copper ions don't simply fly apart as one might expect. They're immersed in a sort of soup of free electrons. The mutual attraction between the positive copper ions and the negatively charged electron mass around them holds the whole substance together by "metallic bonding."

That same soup of free electrons, unattached to specific atoms, flows as an electrical current through a metal when it's connected to a source of electrical pressure. We measure that pressure in volts, and measure the current it creates in amperes.

The more free electrons available in a given material, the more readily they'll move in response to a given electrical pressure; the more free electrons in a material, the less "resistance" it'll have to the flow of those electrons as electrical current.

Materials containing large numbers of free electrons, and therefore offering little resistance to the flow of electron current, are called "conductors." Those with very few free electrons will inevitably have a high resistance to the flow of electron current, since there are only a few available electrons to participate in the process. These materials, due to their high resistance, are good insulators.

Metals in general, because of metallic bonding, have many free electrons and are good conductors. Glass, rubber, wood, cloth, and plastics, having few free electrons, are good insulators. A few materials exist that don't fall into either conductors or insulators. They have some of the characteristics of both, so they're called semiconductors. Silicon and germanium are two. These types of materials are used in various electronic devices, but not directly in building wiring; so they won't concern us.

Static Electricity

Under normal conditions, the atoms of a substance are neutrally charged, since the negative charges of the orbiting electrons are exactly balanced by the positive charge of the protons in the nucleus. When two

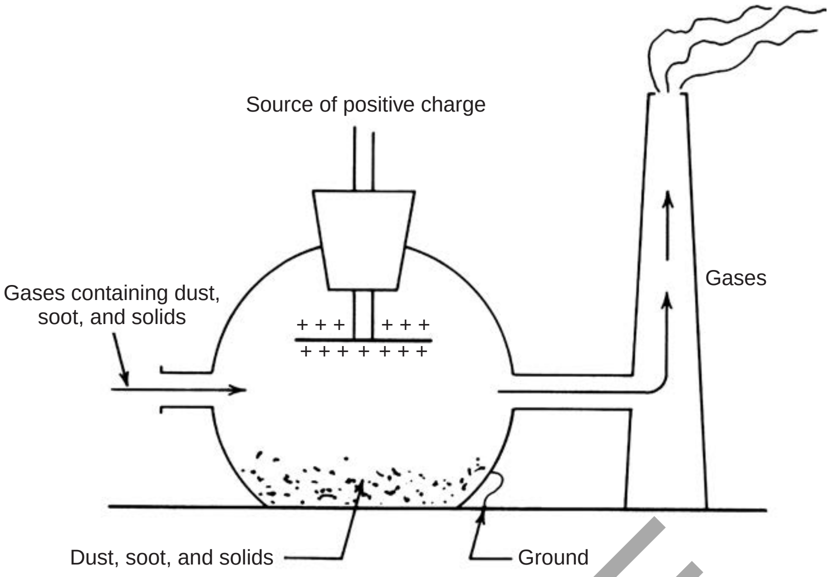

Figure 1-3
Smoke precipitator

electrically unbalanced atoms bond ionically to form a molecule, that molecule also becomes neutral, since the net positive charge of one atom has been offset by the net negative charge of the other.

However, when an outside influence forces many atoms of a material either to gain or lose an electron, that material either becomes negatively or positively charged. This charge collects on the object's surface and tends to stay there until it's conducted away. The pieces of amber that were rubbed with cloth by the Greeks in 600 BC were charged in this way. When you walk across a thick carpet and touch a door knob, the small spark you receive is the same kind of charge. This type of surface charge is called a *static charge*.

One important use of static electricity is in cleaning solid pollutants, such as soot and dust, from the exhausts of industrial plants. We rarely see black smoke belching from factory smoke stacks the way we used to. Now, those gases are vented into a *precipitation chamber*, where a positively-charged plate attracts the solids suspended in the gas. The moment they touch it, they become positively charged and are strongly repelled. They then drop to the bottom of the chamber, where they are collected and disposed of safely. See Figure 1-3.

A more familiar application is a do-it-yourself powder coating that also uses static electricity. You can powder-coat parts with equipment available at local discount tool suppliers. The powder paint is sold online and can be cooked in a home oven.

While this and a few other constructive uses of static electricity exist, the static form is generally useless because it's essentially an instantaneous rather than a steady, dependable force.

Current Electricity

When a neutral atom loses an electron it becomes a *positive* ion. A neutral atom that gains an electron becomes a *negative* ion. Between any two charged particles, a force field exists in which like charges are repelled and unlike charges are attracted. This force field is called an "electrostatic field." In response to the force being exerted by the field, charged particles move. This movement constitutes an electrical current. In a solid conductor, the only mobile particles are free electrons that have escaped from the outer shell of an atom, leaving it as a positive ion. In liquids and gases, the positive ions are also free to move. This effect is encountered with certain types of lighting equipment.

> *"One volt is defined as the pressure necessary to force one ampere of electrical current through a resistance of one ohm."*

When an excess of electrons causing a negative charge is built up at one end of a conductor, and a deficiency of electrons causing a positive charge is built up at the other end, the pressure caused by the field existing between the two ends will cause the loose electrons in the conductor to flow from the area of excess to the area of deficiency, if permitted to do so. As the electron differential between the area of excess and deficiency increases or decreases, the pressure differential between them varies as well.

The difference in electrical pressure between two points is measured in units called volts. The volt is named after an 18th century Italian experimenter named Alessandro Volta, the inventor of the battery. One volt is defined as the pressure necessary to force one ampere of electrical current through a resistance of one ohm. This definition isn't too helpful until we understand what is meant by *ampere* and *ohm*.

The ampere, the unit used to measure current flow, is named in honor of Andre Marie Ampere, also a late-18th century electrical experimenter. His experiments dealt in part with the flow of current in a conductor. Since an electrical current consists of a flow of electrons through a conductor, then the measurement of that flow is a count of the electrons passing a designated metering point in a specific length of time. As a comparison, amperage measures the flow of electricity per second the same way gallons per minute measures the flow of water. An electrical flow of 6,250,000,000,000,000,000 electrons per second equals one ampere, and that's what a pressure of one volt will push through a resistance of one ohm.

For an electrical pressure (voltage) to push a current (amperage) through any substance, that voltage must be sufficient to overcome the resistance of the substance. All substances have some kind of resistance to the flow of electrical current. Conductors, such as metals, have low resistance. Various insulators, such as plastics, paper, glass, or rubber, have high resistance, but no material exists that has no resistance. Since the resistances of different materials vary so widely, it's necessary to have a means for measuring these differences.

It was internationally agreed on long ago to accept a unit called the ohm as the measure of resistance. The ohm is named after another late-18th and early-19th century investigator of electrical phenomena, Georg Simon Ohm. Ohm recognized resistance as an inherent property of all materials. He also worked out *Ohm's Law* that explains the relationship among voltage, amperage and resistance.

Ohm's Law

Ohm's Law states that an absolute fixed relationship exists between current, voltage, and resistance such that the current flowing in a circuit is directly proportional to the applied voltage, and inversely proportional to the resistance. Expressed in words, this sounds rather complicated, but it can be reduced to a very simple and easy to understand mathematical formula. This formula can be stated three ways. For mathematical purposes, the following symbols are used:

- Electrical current in amperes = I
- Electrical pressure in volts = E
- Electrical resistance in ohms (Ω) = R

1. The current in amperes is equal to the pressure in volts divided by the resistance in ohms.

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

2. The resistance in ohms is equal to the pressure in volts divided by the current in amperes.

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

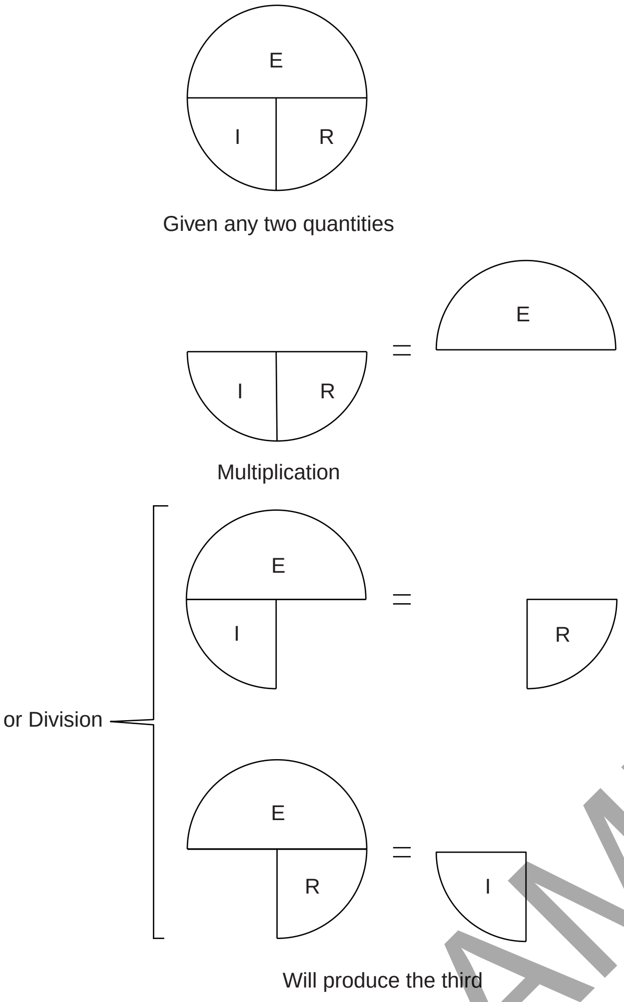

Figure 1-4
Ohm's Law

3. The pressure in volts is equal to the current in amperes multiplied by the resistance in ohms.

$$E = I \times R$$

With any two factors known, the third can easily be calculated by either division or multiplication. All that's necessary is to keep track of when to multiply and when to divide. Use the diagram shown in Figure 1-4 as a guide.

EXAMPLE Using Ohm's Law, a device with a resistance of 18 ohms will be connected to a 120-volt circuit. What amperage will it draw?

$$I = \frac{E}{R} = \frac{120}{18} = 6.6667 \text{ amperes}$$

EXAMPLE One of the countertop appliances draws 4 amperes at 120 volts. What is its internal resistance?

$$R = \frac{E}{I} = \frac{120}{4} = 30$$

EXAMPLE An electric dryer has a resistance of 10.67 and draws 22.5 amperes. What voltage should be supplied?

$$E = I \times R = 10.67 \times 22.5 = 240 \text{ volts}$$

An ohmmeter can be used to read resistances directly, but only when the circuit is off. However, many electrical devices show very little resistance when turned off and cold, but will increase in resistance dramatically when they're turned on and hot. A broiler, toaster, or tungsten light bulb are examples of this. A 60-watt tungsten light bulb has a cold resistance of only 5 ohms. A resistance of 5 ohms with a pressure of 120 volts would mean that a current of 24 amperes would be drawn by that bulb.

$$I = \frac{120}{5} = 24 \text{ amperes}$$

What actually happens is completely different. The filament heats instantaneously, which increases its resistance instantaneously from 5 ohms to 240 ohms. This resistance, however, can be found only by computation rather than direct measurement. This particular computation requires using another formula in addition to Ohm's Law. This one is known as Watt's Law and it was formulated by James Watt.

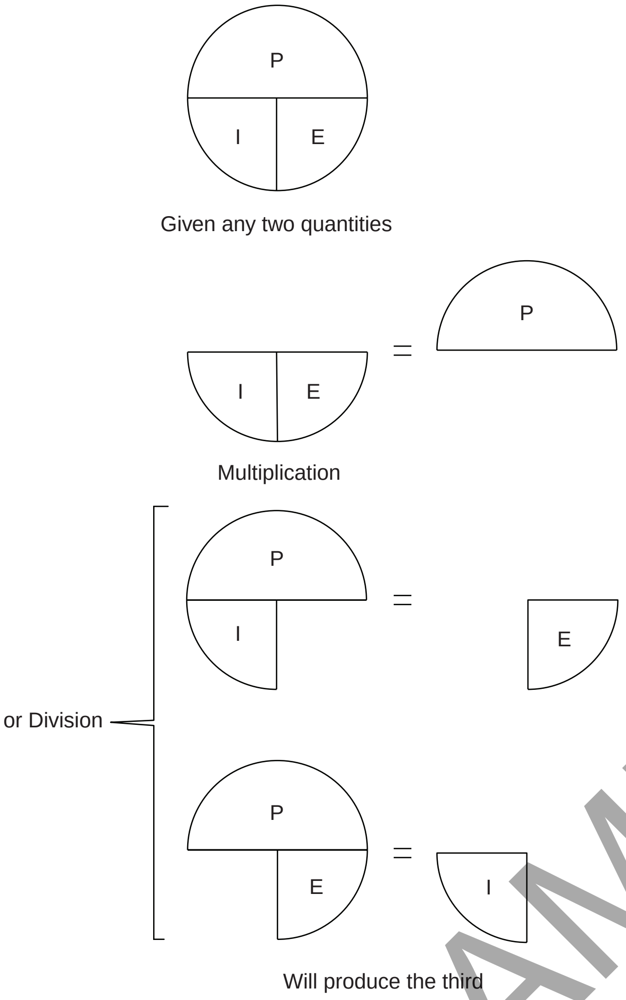

Figure 1-5
Watt's Law

Watt's Law

This law is named after the same James Watt who invented the reciprocating steam engine. After creating his invention, he found it difficult to sell it to a skeptical public until he could work out a way to compare its performance with that of a horse — horses being the high-power engine of the time. The horsepower ratings for not only steam engines, but also gasoline, diesel, and electric motors are derived from his basic formulations.

Just as a fixed relationship exists in Ohm's Law between voltage, amperage and resistance, so in Watt's Law a fixed relationship exists between power expressed in watts, amperage, and voltage. Watt's Law states that the power available in watts is equal to the amperage multiplied by the voltage.

$$P = I \times E$$

There are two other common versions of this formula. One is that the current in amperes is equal to the power in watts divided by the voltage.

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

The other version is that the voltage is equal to the power in watts divided by the amperage.

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

As with Ohm's Law, when any two quantities are known, the third is obtained by simple multiplication or division. This method also applies to Watt's Law.

Watt's Law provides a simple method for converting watts to equivalent amperage, and vice versa. See the diagram in Figure 1-5. This type of computation is needed to determine connected loads on circuits, as we'll discuss in Chapter 8. Loads must be known accurately in order to insure that proper wire and breaker sizes are specified. Load computations are also used in troubleshooting to determine when a circuit is overloaded, and to help determine proper action when an overload is found.

EXAMPLE A 1 horsepower electric motor draws 746 watts of power at 120 volts. Will it operate satisfactorily on a 15-ampere circuit?

$$I = \frac{P}{E} = \frac{746}{120} = 6.22 \text{ amperes} \qquad \text{No problem!}$$

EXAMPLE A coffee maker drawing 1000 watts, a toaster at 1200 watts, and an electric skillet at 600 watts are all plugged into a 20-ampere, 120-volt countertop appliance circuit. Any two will operate satisfactorily, but as soon as the third one (no matter which one it is) is turned on the breaker trips. What is the matter?

$$P = I \times E = 20 \times 120 = 2{,}400 \text{ watts}$$

That's the maximum the circuit can handle. Above that wattage the breaker should trip. Let's look at the combinations:

Coffee maker	1,000	
Toaster	1,200	
Total	2,200	No problem
Coffee maker	1,000	
Electric skillet	600	
Total	1,600	No problem
Toaster	1,200	
Electric skillet	600	
Total	1,800	No problem
Coffee maker	1,000	
Toaster	1,200	
Electric skillet	600	
Total	2,800	Overloaded by 400 watts

Electrical Measurements

Electricians wiring residences or other small buildings actually take very few electrical measurements. However, when they need a measurement, they must know what instrument to use and how to use it. The workhorse of an electrician, and most commonly-used instrument, is the digital multimeter shown in Figure 1-6. This instrument gives readings in Alternating Current (AC) volts, Direct Current (DC) volts, ohms (resistance), or milliamperes. Prices for a digital multimeter vary from as little as $30 for a basic model to as much as $1,000 for a top-of-the-line, high-precision one.

I prefer an analog multimeter, rather than the digital-display multimeter. A digital multimeter requires a battery for both the display and the ohmmeter to work. With an analog display meter, the AC, DC and amperes display work, and no battery is required. A battery is required only for the ohmmeter function. Why should you care? It comes down to the reliability and availably of batteries. Some construction jobs are rural, and it may be a long way to go for batteries if you forget to bring along some spares. When using a digital multimeter, a dead battery means a totally dead meter.

The precision of the more expensive instruments isn't necessary for building wiring. A small, inexpensive instrument is ideal. In fact it's preferable, since it's compact enough to carry in a pocket while squirming in and out of nooks and corners during your normal work day. If it's accidentally smashed in the process, you haven't lost much.

The multimeter has a central function selector switch to shift among the various AC, DC, ohms, and milliampere scales. In normal building wiring, you only use AC voltage and ohms scales. AC voltages in a building will be either 120 nominal, or 240 nominal. *Nominal* means that the actual voltage at any given time might vary anywhere between 110 volts and 120 volts, or between 220 volts and 240 volts. When reading building voltages, make sure the selector switch is set to AC. If the multimeter selector is accidentally set to DC, and you're reading a receptacle that has 240 volts AC, then you'll get a faulty reading of "0" volts because there's no *DC voltage* at that point. Your instrument will give you a correct reading if you enter accurate information. If you try to get a DC voltage reading from an AC outlet, the multimeter will correctly read "0." If you try to get an AC voltage reading from a car battery, the correct reading will also be "0."

Always remember — safety first. When using a multimeter, confirm that the meter is working *before* you trust it with your safety. Check the meter on a circuit you know is hot to be sure it's functioning properly and to confirm it's reading the voltage. If you need to de-energize a circuit, it's a good idea to have another person work the breaker or switch feeding the circuit you're testing to see if the voltage goes to zero when the switch is turned off.

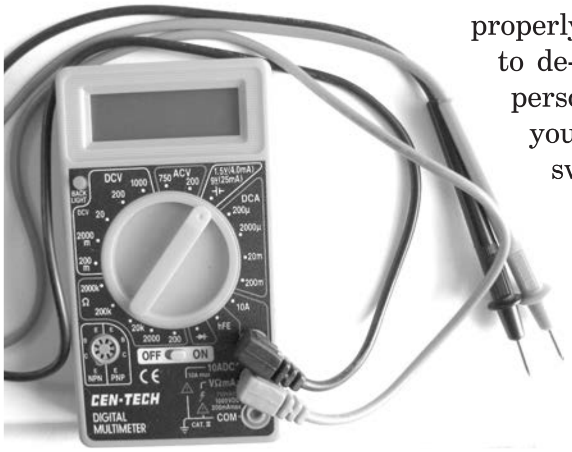

Figure 1-6
Digital multimeter

The ohms scales on a multimeter are primarily used to check circuit continuity, and to test for shorts. When using the ohms scales, *be sure the power is off*. Resistances can't be read on a live circuit, only on a dead one. If power is on, it'll burn out the meter. After setting the selector to ohms, and before taking any readings, short the test probes to each other, and use the "ohms adjust" control to set the meter accurately on "0." If you don't do this, you might receive misleading readings.

Figure 1-7
Clamp-on field-sensing ammeter

An amperage measurement isn't usually necessary when wiring small buildings. However, it's a very helpful measurement to have for troubleshooting, such as when tracking an overload that keeps tripping a breaker. The instrument you need for this is a clamp-on field-sensing ammeter, like the digital-display ammeter shown in Figure 1-7. Analog display ammeters that don't require batteries are also available. This meter, when clamped around the power lead from a breaker, will detect the electrical field around it and translate the intensity of that field into a measurement of the amperage flowing into that wire. In order to read amperage, you must clip the meter around the hot wire only. If it's clipped around the complete cable feeding an appliance, it'll read "0" instead of the amperage being drawn by the appliance. The reasons for this will be discussed in the next chapter. To read the exact amperage drawn by a plug-in appliance, you need an adapter to separate the hot wire from the common in the appliance feed.

Figure 1-8
Watthour meter

Besides voltage, resistance and amperage, wattage, the fourth factor in electrical computations, can be directly measured with — you guessed it, a wattmeter. The wiring of buildings we'll be discussing here doesn't require this measurement since wire sizing, breaker sizing, and circuit loading are specified and limited in the electrical code by amperage rather than wattage. Probably the only contact the average electrician has with wattage measurement is the installation of the meter box in the service entrance. See Chapter 9. That's where the utility company mounts their watthour meter to record electrical power usage for billing purposes. See Figure 1-8.

Basic Electrical Circuits

Since an electrical current will flow readily through a conductor, it's a simple matter to direct electrical energy from a remote source to a desired point by connecting conductors to form a low resistance path from one point to the other. Conductors connected this way become an electrical circuit. The simplest electrical circuit consists of a minimum of four parts, as shown in the diagram in Figure 1-9. They are: a source of electrical pressure, or voltage; conductors to connect the source to the use point;

an electrical load or using device; and a switch or other mechanism to control that load. Since a current will only flow when the path is complete, from the high pressure, or hot side, of the source back to the low pressure, or grounded side, you also need a return conductor to complete the circuit.

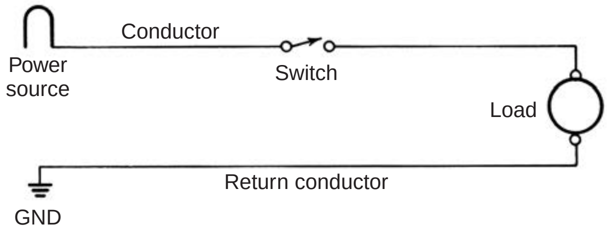

Figure 1-9
Basic electric circuit

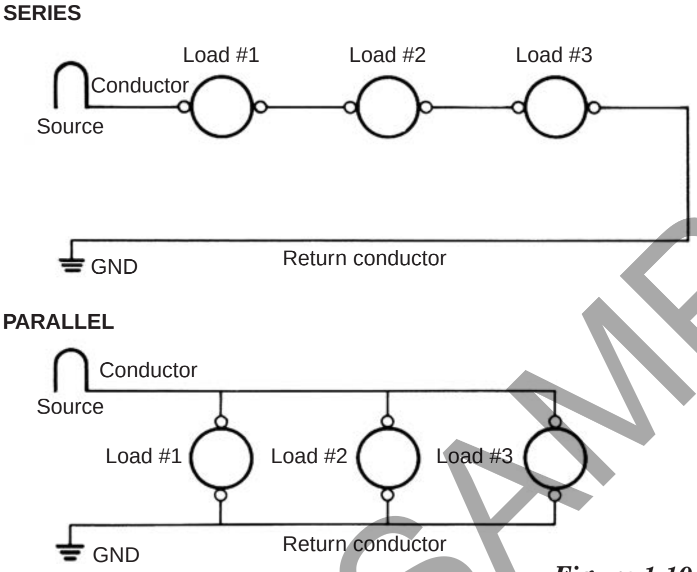

Figure 1-10
Series and parallel circuits

Electrical loads can be connected to a power source in either of two ways. See the diagram in Figure 1-10. They can be connected in *series* or in *parallel*. With a series circuit, there's only one path through which current can flow, so the same amperage flows through all parts of the circuit. In a parallel connection, there's a separate electrical path through each load with part of the amperage coming from the source passing through each path. The part of the total amperage drawn that passes through each load is proportional to its wattage and inversely proportional to its resistance.

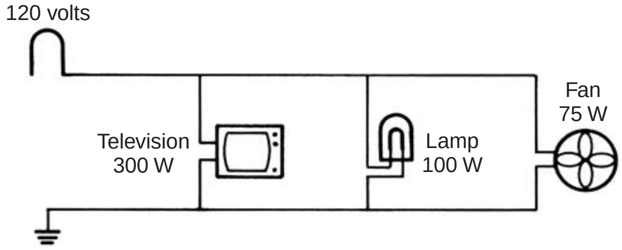

Figure 1-11
Three loads in parallel

Figure 1-11 shows three loads connected in parallel on one circuit. The total wattage drawn is the sum of the three loads:

Television	300 watts
Lamp	100 watts
Fan	75 watts
Total	*475 watts*

Using Watt's Law, you can determine the total amperage being drawn:

$$I = \frac{P}{E} = \frac{475}{120} = 3.958 \text{ amperes}$$

The amperage being drawn by the television alone is:

$$I = \frac{P}{E} = \frac{300}{120} = 2.5 \text{ amperes}$$

And, its resistance calculated using Ohm's Law is:

$$R = \frac{E}{I} = \frac{120}{2.5} = 48 \text{ ohms}$$

In contrast, the amperage being drawn by just the fan is:

$$I = \frac{P}{E} = \frac{75}{120} = 0.625 \text{ amperes}$$

But its resistance is much greater:

$$R = \frac{E}{I} = \frac{120}{0.625} = 192 \text{ ohms}$$

Something else is happening in this parallel circuit that'll help you understand overloads. The total resistance on this circuit (look again at Figure 1-11) using Ohm's Law, is:

$$R = \frac{E}{I} = \frac{120}{3.958} = 30 \text{ ohms}$$

IF YOU HAVE PROBLEMS remembering series vs. parallel, here's something that may help. Many Christmas tree light strings used to be wired in series, so if one or more bulbs burned out, the whole string would be out. About the only way to fix it was to start at one end and replace each bulb, one-by-one, with a bulb you knew was working until the whole string lit up again. Then you'd know that the last one you replaced was the culprit.

Now, we already have a resistance of 48 ohms, and another of 192 ohms. We haven't calculated the third one, but we know it'll be somewhere between the two figures. How can the total resistance of the circuit be only 30 ohms? The truth is, in parallel circuitry the current may pass through multiple paths. Regardless of how high the resistance of an individual path is, once that path exists, *some* current can pass through it — current that couldn't and wasn't passing through other existing paths. Therefore, the more paths available, regardless of how high their resistances are, the more current the circuit allows to pass through, because at the opening of each new path the total resistance of the circuit is reduced.

In building wiring, all power-using devices are wired in parallel to keep each one independent of the others. Look at the series circuit in Figure 1-10. If Load #2 were to break down, both #1 and #3 would stop because the only existing electrical path is broken. If Load #2 in the parallel circuit failed, it wouldn't affect either #1 or #3, because each has independent access to the power source.

In building wiring, the basic rule is: "All loads are wired in parallel; all switches are wired in series." A switch completes or breaks an electrical path, but it doesn't use any power. It offers either no resistance, or infinite resistance to the passage of an electrical current. Its purpose is merely to open or close the path to some electrical equipment.

Effects of Electrical Energy

Electrical energy can easily be channeled to produce heat, magnetism, chemical reactions, and even physiological effects as well. All of these effects involve the conversion of energy from one form to another. Such conversions always involve some loss.

Mechanical energy applied to an apparatus encounters resistance in the form of friction within the mechanism. When transmitting power from the engine to the wheels of an automobile, some of that power, despite the best lubrication, is lost in friction. Actually, it isn't lost; it's still present as heat that develops at friction points. A transformation of mechanical energy into heat energy takes place.

Similarly, electrical energy is transformed into heat in the process of overcoming the resistance in a conductor. Conductors specifically designed to maximize this transformation are used in the heating elements of certain electrical appliances, such as toasters, broilers, electric ranges, water heaters, clothes dryers, and other electrical heating equipment. These are all common uses of the heating effect that can be produced with electrical energy.

The incandescent light bulb is another, but less common, example of the heating effect of electricity. Inside the bulb, an electrical current passes through a filament of tungsten wire. The resistance of the wire causes it to heat white hot, producing light. This process produces considerable unwanted heat, or "waste heat," as you'll notice if you touch a burning bulb.

The fluorescent light shown in Figure 1-12 is another example of the heating effect of electricity. In this case, filaments don't produce light, but act as heaters and ionizing electrodes. Air is pumped out of a fluorescent tube, then a bit of argon gas and a few drops of mercury are introduced. The heater current passing through the filaments vaporizes the mercury. The higher ionizing voltage then ionizes first the argon, then the mercury vapor,

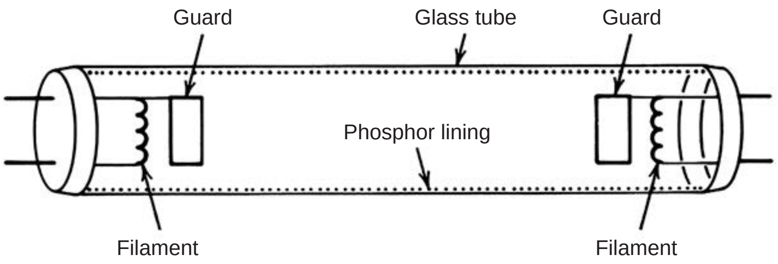

Figure 1-12
Fluorescent tube

producing ultraviolet light. The ultraviolet hits the phosphor coating of the tube, producing visible light. The fluorescent tube is a far more efficient light than the incandescent, as a much higher percentage of the electrical energy used appears as visible light and far less is wasted in heat. Touch an operating fluorescent tube and you'll feel the difference.

Other electrical lighting systems such as neon, metal halide, sodium vapor, LED, and mercury vapor lamps are all examples of electrical heating effects.

In addition to producing heat, electricity can be used to produce many other useful results through magnetic effects. As we'll discuss in Chapter 2, a magnetic field can produce an electrical current. The reverse is also true. An electrical current can produce magnetic effects. The electric motor in its many forms is probably the most important use of the electromagnetic effect, but there are many others.

Some examples of other everyday items whose operation is based on magnetism are doorbells, buzzers, telephone transmitters and receivers, solenoid controls, electromagnets, dynamic stereo loudspeakers, and all material recorded on magnetic tape.

> *"The fluorescent tube is a far more efficient light than the incandescent, as a much higher percentage of the electrical energy used appears as visible light and far less is wasted in heat."*

The chemical effects of electricity aren't as commonly encountered as heating or magnetic effects; an example is electroplated silverware. An electro-chemical effect in a car battery produces the power to turn the car engine over every time it's started. The dry-cell batteries used in flashlights are also examples of chemical-effect items.

The physiological effects of electricity usually aren't the ones we're most eager to encounter. However, while we tend to think of these effects as generally unpleasant, some are extremely useful. For example, the pacemaker that many heart patients depend on regulates the heartbeat electrically. The lifesaving defibrillators in coronary care units are also very important in regulating the heart. The medical arsenal contains many other important pieces of electrical equipment for saving lives and improving patient comfort.

In Summary

We now know some of the basic facts about electricity. We know it flows easily through metallic substances that contain an abundance of free electrons. We know its pressure is measured in volts, its current flow in amperes, and the resistance to its flow is measured in ohms. We have seen that there are two types of electrical current: direct and alternating. We know of two types of electrical circuits — a series circuit provides only one path for the electrical current to take, while a parallel circuit provides alternate paths for the current. In addition, we now know that electricity can produce chemical and magnetic effects, as well as the physiological effects. In the next chapter we'll see how electric power is produced.

STUDY QUESTIONS

1. How many possible electron shells can an atom have?

A) 4
B) 5
C) 7
D) 9

2. What type of resistance to the flow of electrical current will a material containing an abundance of free electrons have?

A) Negative
B) Positive
C) Very high
D) Very low

3. Which is a practical use of static electricity?

A) Drycell battery
B) Exhaust cleaners on industrial plants
C) Carpet-cleaning attachment on a vacuum cleaner
D) Defibrillator in coronary care units

4. What unit is used to measure electrical current flow?

A) Ampere
B) Ohm
C) Volt
D) Watt

5. How many amperes will be drawn by a device with a resistance of 30 ohms connected to a 120-volt circuit?

A) 4
B) 30
C) 40
D) 360

6. **Which electrical formula was devised to show the relationship between power, amperage and voltage?**
   - A) Ohm's Law
   - B) Watt's Law
   - C) Power Conversion Formula
   - D) Fulton's Law

7. **Which of the following won't a multimeter measure?**
   - A) AC volts
   - B) DC volts
   - C) Watts
   - D) Ohms

8. **Which formula will give the total resistance of a parallel circuit?**
   - A) The voltage divided by the amperage being drawn
   - B) The voltage multiplied by the amperage being drawn
   - C) The sum of the resistances of the devices connected
   - D) The sum of the resistances divided by the voltage

9. **Which of the following is true regarding how all power-using devices in a building are wired?**
   - A) Depending on the use, they may be wired either in parallel or in series
   - B) They are wired in series to keep each independent
   - C) They are wired in parallel
   - D) If wired in parallel, each device must be independently grounded

10. **Which of the following groups contain *only* examples of devices using the magnetic effects of electricity?**
   - A) Doorbell, drycell battery, electric motor
   - B) Doorbell, electric motor, fluorescent light
   - C) Drycell battery, incandescent light, telephone receiver
   - D) Electric motor, stereo loudspeaker, telephone transmitter

Answers to Chapter Questions

Following each answer is the page (or pages) in the book where the subject of that question is discussed. It's sometimes necessary to read through more than one page when the question asks for a concept, rather than a specific point.

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