THE 12-VOLT BIBLE FOR BOATS SECOND EDITION

MINER BROTHERTON

REVISED BY ED SHERMAN

DRAWINGS BY MICHAEL BLASER

*I dedicate this book to the memory
of my first mate of many years,
SHIRLEY (1929–2002),
a loving wife, a caring mother,
an ideal cruising companion,
and a willing participant
in all my life's activities.
But best of all, she put up with me
for more than fifty years.*

Blank
iv

CONTENTS

ACKNOWLEDGMENTS

Cruising World for their encouragement in selecting and publishing some of my articles, and I thank Jim Gilbert of Seven Seas Press for asking me to do this book.

<div align="right">MINER K. BROTHERTON, 1985</div>

I'd like to thank my friends at Marinco Guest for providing me with updated photographs of electrical equipment and gear for this second edition of *The 12-Volt Bible for Boats*. I'd also like to thank the folks at Rolls and East Penn (Deka) Battery Companies for their updated photos and data describing the new battery technologies discussed in this second edition. Perhaps most important, I'd like to thank the many students who have attended the various electrical training courses I've offered for the American Boat and Yacht Council. I suspect that they have no idea how much I learn from each of them as I teach these programs. Some of that knowledge is passed along in this book as well as the articles I write for such publications as *Cruising World* and *Professional Boatbuilder* magazines. Thanks to all!

<div align="right">ED SHERMAN, 2002</div>

INTRODUCTION TO THE SECOND EDITION

BY ED SHERMAN

When Miner published the first edition of *The 12-Volt Bible for Boats* in 1985 we were on the threshold of some major technological developments that have changed the boating world, at least as far as marine electrics is concerned. The foundation material found in the first edition remains unchanged—things like Ohm's Law, electric currents, and the interactions of the "players" in this game of electro-magic are still the same. The basic methods of troubleshooting are also still valid, but the equipment available for this endeavor has advanced significantly. In some cases, things have actually gotten a bit simpler. Things like the inductive ammeter have made some troubleshooting procedures a simple one-step process. As for the equipment we install on our boats, advances like GPS for navigating, gel-cell batteries, and the newest AGM (absorbed glass mat) technologies have gone a long way toward making boating simpler and more enjoyable. So, as you read through this second edition of *The 12-Volt Bible for Boats*, look for the following:

- updated material in the troubleshooting section that reflects the changes in multimeters now available
- changes in the sections discussing batteries and their needs
- changes in the equipment discussed—multistage battery chargers and DC-to-AC inverters, for example
- changes in the types of circuit protection now available
- changes in some of the hand-tools we use to perform basic tasks such as wire crimping and stripping

I hope you enjoy this second edition of *The 12-Volt Bible for Boats* and find it a useful tool in your on-board arsenal of electrical troubleshooting equipment.

INTRODUCTION TO THE FIRST EDITION

BY MINER BROTHERTON

Welcome aboard *The 12-Volt Bible for Boats*. Basically, this is a nuts-and-bolts primer, an elementary textbook for boatowners who are not skilled electricians.

By profession, I am a teacher of physical science. By choice I am a boatowner, marine writer, scientist, boatbuilder, environmentalist, confirmed cruiser, licensed vessel operator, one-time boat salesman, and former airplane and helicopter mechanic and flight crew member. But most of all, I like to just plain mess around with boats. That includes doing all my own work on board our Colvin-designed gaff schooner, which my wife and I completed from a custom fiberglass hull and deck by Al Vaitses; so I have had to teach myself lots of different skills, including boat electricity.

In doing this I have relied on the printed work of many others. No one is born with electrical knowledge; you have to learn it someplace. However, I have found that some books like this are written by engineers who seem to forget that most of us are lawyers, accountants, English teachers, psychologists, and musicians. What do we know about power factors, zener diodes, and squirrel cage rotors? Some others start out very basic, but soon become super-sophisticated in subject matter.

Without my background in physics and physical science, I'm sure I would not have been able to follow all their explanations.

Of course, there is no guarantee you will be able to follow all of mine, but at least I will remember who most of you are, to make this a book you will want to carry on board with you.

I won't show you how to repair your GPS or install a radar; but I will tell you how your 12-volt DC electrical system works, what you should do to maintain it in good operating condition, how to recognize when you have an electrical problem, how to troubleshoot to locate the problem, and what simple tools and techniques you'll need to fix common electrical system problems.

Some complex problems are just better left to professionals. But when your running lights quit while you're crossing a shipping lane 50 miles from the nearest marina, it is essential to know where to look to try to get them working again. If this little book helps to accomplish that, then the effort put into it will have been worthwhile, and you will have invested your money wisely.

BASIC THEORY OF ELECTRICITY

A PRIMER

A FEW WORDS OF CAUTION

Right up front here, I should say a few words about precautions and haz-ards. I know the title indicates our coverage will be limited to 12 volts DC, but that does not mean that we can treat the system with a cavalier attitude. Even though we can get 12 volts from a handful of AA flash-light cells (eight, to be exact), this does not imply in any way that we can ignore basic safety standards and practices, which are prescribed by such organizations as the American Boat and Yacht Council Inc. and the National Fire Protection Association. There is good reason for these high standards—survival—your survival and the survival of your boat-ing companions. Safety and survival are the names of the game.

An overloaded, unprotected circuit can generate tremendous heat, which may melt the wire's insulation or even start a fire. An arcing switch, relay, or motor can ignite explosive vapors that may have col-lected in the bilge or any closed compartment, with disastrous results. Electrical leaks and stray electric currents can destroy a boat or its

equipment by electrolysis. It is true that you are much less likely to be shocked by your boat's electrical system than you are by your house wiring or by the marina shore power box on your slip, but there is a lot more to safety than avoiding shocks.

Most of the hazards associated with our system can be found in the battery compartment. If you have ever accidentally dropped a screwdriver or long wrench on a storage battery so that it hit both posts or terminals, you know what I mean—sparks fly and the tool has a permanent gouge or two at the points of contact where the metal melted away. Or maybe you saw the sparks fly while you were hooking up a pair of jumper cables to start your car when its battery was down. Even though there are only 12 volts, very large currents and significant energy are involved.

While your batteries are being charged, especially near the end of the charging cycle, oxygen and hydrogen gases are produced from the electrical dissociation of water. They form a particularly hazardous explosive mixture if allowed to accumulate in a confined space aboard. A single spark under the right conditions could trigger a boat-and-flesh-damaging explosion.

Finally, there is the hazard of the battery electrolyte, a sulfuric acid solution. Spill it on your clothes and it will eat holes in them. Spill it on your skin and you'll get severe burns unless it's washed off immediately and neutralized with an alkaline solution such as baking soda (sodium bicarbonate). Spilling the acid in your eyes can lead to severely impaired vision or even blindness. Be especially careful with your eyes. Don't look closely into the filler holes to check for liquid level while the battery is charging; a rising bubble can easily pop and splash acid into your eyeball. Use a flashlight and look from a distance. Use eye protection goggles or glasses whenever possible. These are grim scenarios, I know. I am trying to frighten you a little, but only to make you aware of the potential hazards. A 12-volt DC system is *not* inherently safe. It is *relatively* safe, but it does demand your attention and your respect.

THE ATOM AND ITS ELECTRONS

It should stand to reason that if ever we hope to comprehend how our boat's electrical system works, we must have some knowledge of the basic theory behind it. Unfortunately, electricity almost defies description. It is fairly easy to say how it behaves, what it does and does not do, and how we use it; but because we cannot see, touch, taste, smell, or hear electricity, it appears all the more mysterious to us.

THE ATOM

In order to trace this elusive stuff, we have to start with the atom—the basic building block of every element—because that's where electricity begins. As strange as it may sound at first, an atom consists mostly of empty space—even the heaviest and the hardest of atoms. This space is very sparsely occupied by electrons, protons and neutrons. In simplest terms, electrons are the smallest quantities of electricity, and for purposes of this book are regarded as *particles*. The central core of the atom consists of protons and neutrons, which provide most of the mass of the atom. Each neutron (uncharged) and each proton (one positive charge per proton) weighs about 1,800 times as much as an electron, which carries a charge equal and opposite to that of the proton; i.e., it is negatively charged. Again without getting too fancy about it, let's just say that the electron is in an orbit of rather large radius. The atoms of the various elements, such as hydrogen, oxygen, lead, iron and so on, contain characteristic numbers of these particles; that's what distinguishes one from another. Hydrogen is the simplest; it owns just one proton and one electron orbiting around it. Moreover, this electron can be pulled away under the right conditions, leaving a bare proton with its positive charge. This is now called a positive "ion," while the flight of the electron up, up, and away constitutes an electric current.

The sketches in Figure 1-1 cannot do justice to scale. Imagine a

HYDROGEN   LITHIUM   NITROGEN

FIGURE 1-1

domed football stadium with a ball bearing sitting on the 50-yard line and some mosquitoes flying around the rafters. The ball bearing is the nucleus and the mosquitoes are the electrons—almost to proper scale!

ELECTRONS

It's those little, nearly massless, negative charges that whirl about the nucleus at extremely high speeds—in certain orbits or "energy levels"—those mosquitoes in the rafters, that we are interested in. The electron is the basic "grain" or unit of electricity, and all electrons belong to atoms. All electrons are identical, no matter which kind of atom they come from. Each has the same amount of negative electrical charge and the same little bit of mass. Atoms themselves are always electrically neutral; that is, they have just as many positive charges in the nucleus as they do negative electrons whirling about them. If an atom, or group of atoms, loses or gains one or more electrons, it becomes charged, either positively or negatively, and is then called an *ion*.

MOLECULES AND BONDING

Atoms join themselves together to form larger structures called *molecules*; these may involve the same or different kinds of atoms. Molecules are held together by the electrons rather than by the nuclei, and

the name given to the holding mechanism is *bonding*. Electrons are arranged in several different configurations in order to accomplish the bonding function.

If an electron is actually transferred from one atom to another, the bond is called *ionic*. Of course this means that both atoms become ions as soon as the transfer occurs. One gains an electron to become a negative ion, and the other loses an electron to become a positive ion; the resulting attractive force between them makes this an extremely strong bond. Should this molecule ever separate, the ions are already there. Most salts, including common table salt, the major dissolved constituent of seawater, are held together with ionic bonds.

Sometimes two or more atoms are held together by a sharing of one or more of the outermost electrons. Now these electrons will orbit about the whole group, rather than their own homebase-atom, and thus "glue" it all together. Such bonding is called *covalent*. When either covalent or ionic molecules dissociate, or come apart, in a solution, they separate into two subgroups, each having the opposite charge. Thus H_2SO_4, sulfuric acid, in our battery becomes 2 H (+) and SO_4 (2 −). Later we'll see why that is important. When ions move, they carry their respective charges with them. This is what constitutes the electric current inside a storage battery.

Atoms that make up our copper wires also share electrons, but in a different way. When a metal solidifies from a molten state, the atoms are locked together in what is called a crystalline structure. They are jam-packed so closely together that their electron orbits overlap, forming what is sometimes called an *electron cloud*. Individual electrons no longer belong to specific atoms or groups of atoms; they belong to the whole crystal in the *metallic bond*. The crystal remains electrically neutral, having just as many plus charges as minus ones, but now this cloud of electrons is free to migrate throughout the length of the wire, hooking up with whichever atoms it happens to be near. These are the "free electrons" that make some materials such as copper and silver very

good conductors of electric current. Other substances, lacking them, are poor conductors often called *insulators*.

IONS AND ELECTRONS

In our boat's electrical system we usually find the ions in the battery and electrons in the wires. Chemical reactions take place in the battery that involve the movement of the ions through the liquid electrolyte. As a result of these reactions, electrons enter and leave the ends of the wires and move very quickly around the circuit inside the wires. With a stopwatch, you cannot measure the time between flipping a switch and seeing a bulb light up; it would be only one-hundred-millionth of a second for a 10-foot piece of wire. The electrons don't travel that fast, but the electrical event does. That's because the wire already has lots of those "free electrons" in it. You might liken it to a soda straw completely full of small BBs. Now if you shove one more BB into one end, another will immediately jump out the far end, but it's not the same BB that traveled all the way through the straw. In our boat's electric circuits the electron cloud is set into motion when a voltage is applied to the ends of the conductor. That creates a current. Now we'll have to see what those terms mean.

TERMS DEFINED

COULOMB'S LAW

A basic rule of electricity says that unlike charges ($+$ and $-$) attract each other, and like charges (either $+$ and $+$ or $-$ and $-$) repel each other.

> ***The force of attraction or repulsion between charged bodies is directly proportional to the product of the charges on the bodies and inversely proportional to the square of the distance between them.***

This law dates back to 1789 when the French scientist Charles Coulomb did the original research in the field of static electricity—charges at rest. We're interested in moving charges—current electricity, but Coulomb's Law still applies, even though we won't have to use it for any calculations. That's really about all the theory we need to know in order to begin.

CHARGE

Let's begin with *charge*. The ultimate piece of electricity is the electron, and charge measures how many electrons we're talking about. It is a quantity measure, like a ream of paper, so that's why it is always abbreviated "Q." *Coulomb* is the charge unit, equal to six and a quarter billion billion (6.24×10^{18}) electrons. Fortunately, no one ever has to count them. Besides, we never need to use this unit by itself in boat electricity. It is only when charges start moving that we begin to take notice.

CURRENT

The rate at which charge moves is called *current*. Now that is important to boat electricity. We measure electric current in *amperes*, but everyone says *amps*. By definition, a current of 1 ampere exists in a circuit when 1 coulomb of charge is passing a point every second. Current is the flow rate, just as in a river. Current is always abbreviated "I." So we could say in mathematical shorthand, $I = Q/T$, which means:

> **Current is equal to the amount of charge that moves past a point in a given time interval.**

In some cases the time is more important than the amount of charge. In a lightning discharge, for instance, tremendous currents may be involved, even though the total amount of charge transferred might not be so large at all. The lightning event is over in a few thousandths of a second (milliseconds), so when we divide the charge by a very small time interval, we get an enormous result for the lightning current—values of 60,000 to 100,000 amperes are not uncommon. On your boat, most circuits will have considerably less than 20 amps in them; but not all. Your engine starter circuit can give you a real surprise. Starting currents can be as high as 800 amps for cranking a cold diesel in winter! A warm summer gas engine will draw 150 to 250 amps while starting.

VOLTAGE, POTENTIAL DIFFERENCE, AND EMF

Voltage, or *potential*, is what pushes the electrons through the wires around the circuit. It may be thought of as acting similarly to pressure in a water system—the higher the pressure, the more gallons of water will flow from the hose per minute. The higher the voltage, the greater the current in the wires. Potential is also related to energy in a circuit in this way: Potential = energy/charge, where the energy is measured in *joules*. This is of more interest to theoreticians than to boatowners, but it will help us define some other terms. Potential is measured in *volts*, hence its more common name of voltage, and it is usually abbreviated "V." In our 12-volt system, each coulomb of charge in the current carries 12 joules of energy around the circuit and expends them in doing work. That's because of the way we define the volt:

> **One volt of potential is equal to one joule of energy per coulomb of charge.**

Actually it is the *potential difference* between any two points in the circuit that pushes the charges along; and if there is no difference in potential between two points, there won't be any current. Now we know how a bird can sit on a high-voltage power line without being electrocuted—both feet are at the same potential, side by side, the difference is zero and so is the current. But if the bird stretches its wings far enough to touch another wire at a different potential—*zap!* Just like backyard bug zappers.

EMF stands for *electro-motive-force*, also measured in volts. EMF differs from voltage in that EMF always applies to a source of energy, called a *seat*. On our boat we have two seats of EMF—the battery and the alternator. In any circuit, the seat's function is to maintain a potential difference between the ends of the circuit to cause the current to flow. The seat supplies energy to the charges as they leave it, and the charges dissipate the energy as they travel around the circuit. Another rule of electricity says that the EMF supplied by the seat must be exactly used up as voltage drops around the circuit. Sometimes EMF is abbreviated "E" to keep it separated from voltage "V," even though both are measured in volts. In our water analogy, a seat of EMF would be like a pump, constantly lifting the water at one end to maintain pressure to cause the water to flow through the pipes.

ENERGY

We have already mentioned electric energy in defining the volt. Let's look at it a little more closely, and see if we can't find some other more common units for it than joules, which is not a frequently used term. The joule is not a huge energy unit. It is nearly the same as the work you would do in lifting a pound weight nine inches; so a joule is about ¾ of a foot-pound. Energy and work are interchangeable. Energy makes it possible to do work, even in an electric circuit. It is the energy that the charges carry that is ultimately responsible for causing a motor to spin to

pump out your bilge, to start your engine, to ventilate your engine room, to hoist your dinghy aboard, or to pull your anchor out of the bottom. Electric energy has been converted to mechanical work in each case. At sunset, when you turn on your navigation lights, you see another type of energy conversion. The bulbs glow because their filaments have been heated to incandescence—electric energy has been converted to heat energy, and if the temperature is high enough, light energy will be emitted as well. Your depth sounder functions because electric energy is converted to sound energy by the transducer, a very special kind of crystal. In this case, the sound reflects off the bottom, returns and hits the crystal, which converts it back to electric energy again. Yes, electric energy does work to perform many tasks for us on board.

POWER

But *power* is a handier term to use than energy in describing the work of electrical devices. We define it this way:

Power is the rate of doing work or expending energy.

Symbolically, P = W/T. If one joule of energy is expended in one second, the power is one *watt*. One thousand watts are called a *kilowatt*, and 746 watts are equal to one *horsepower*. These terms are more familiar to us, I know. We buy lightbulbs by their wattage rating, we see kilowatt-hours every month on our electricity bill, and we use horsepower to rate the output of all kinds of engines, from lawn mowers to tugboat diesels. A 25-watt bulb can expend as much energy as a 100-watt bulb, but it will have to be lit four times as long. For the same time interval, the 100-watt bulb will use energy four times as fast as the 25-watt one. Leaving your 100-watt spreader lights on so you can find your boat after an evening of pub-crawling ashore will clobber your battery. We'll see why in a minute.

Power is also equal to the product of current times voltage. Using symbols we have already defined, P = V × I or,

Watts equal volts times amps.

This is one of the most useful formulas we have seen so far, but we more often use it to solve for the current I. Almost all electrical devices will have their power rating indicated on the name plate—they hardly ever tell us what their current demand is. And we need that information in order to choose the proper size wire to hook up the device into a circuit, To get the current, just turn the formula around and solve for I = P/V, or,

Amps equal watts divided by volts.

Now let's look at those spreader lights you were going to leave on. They were 100 watts for the pair. For our 12-volt system, the current that has to flow in order to light them is equal to 100 watts divided by 12 volts, or 8.3 amps. You'll soon see this certainly is not an insignificant amount.

In order to simplify the arithmetic as much as possible, here is the first of our "magic triangles." It shows the relationship between power (P), current (I), and voltage (V) and tells us how to find an unknown value—just cover that one up, and the positions of the other two show the solution. Cover P; V and I are next to each other, multiply. Cover I; P is over V, divide.

Cover V; P is over I, divide. If my oversimplification offends some of you algebra scholars, I might remind you that several generations of U.S. armed forces electricians and electronic technicians learned their trade with the help of magic triangles, so don't knock it.

AMP-HOURS

Closely related to current and power, especially for direct current systems that use a storage battery as the primary seat of EMF, is the concept of *amp-hours*, or the current multiplied by the time it flows. Amp-hours are used to describe a storage battery's *capacity*; how much charge it is capable of storing. It also is indicative of the rate at which a battery can be discharged, although that may be complicated by several other factors. Getting back to those spreader lights again—if you're gone for four hours, the amp-hours used will be 8.3 amps times 4 hours, or 33 amp-hours. If you happen to get caught up in a singing contest someplace and stay an extra couple of hours, you may row home to find your spreader lights barely glowing a dull yellow. If that's your only battery, next morning you may find, in addition to the hangover, that the engine won't turn over. I always use a kerosene anchor light to avoid any prolonged drain on the battery. Even if the engine does crank and kick right off, you'll have to run it nearly three hours to get the battery fully recharged again. More about that later.

RESISTANCE

The last term we have to define is *resistance*, which is the opposition to a current. For reasons that will soon be obvious, resistance is measured in units called *ohms*. While it acts something like friction, resistance actually is caused by the electrons colliding with atoms inside the wire and being slowed down and scattered. Even the best of conductors have some resistance. Others, such as lightbulb filaments, have much more.

> *Resistance always results in the conversion of electrical energy into heat.*

Except in the case of resistance heaters, it represents a waste of energy and an irretrievable loss to the system. The resistance of a wire depends upon three factors:

1. type of metal (its resistivity)
2. length of the wire
3. cross-sectional area of the wire

Since practically all electrical wire is made of copper, we can ignore the first factor. Length of wire is always twice the distance between components—the current has to travel both "there" and "back." Whenever we talk about the "size" of a wire—always in American Wire Gauge or AWG numbers—we have to remember that large numbers are used for thin wires and small numbers for fat ones. If you ever have to replace or add some wiring on your boat, never use anything smaller than Number 16, and that only for low currents and short runs. We'll talk about how to make the actual selection later. Following our water analogy, it is easier for water to flow through a large pipe than it is through a very narrow one; the skinny pipe offers more water resistance. So small wires offer more resistance to the passage of an electrical current.

ELECTRICITY IS NOT WATER, BUT . . .

Now that we have defined all the terms we need, here is a sketch of the complete water-analogy system, and also one of its electrical counterpart (see next page). We should be all done with the plumbing, now. From here on out, it's all electricity. In the next unit we'll describe each of the circuit components in greater detail.
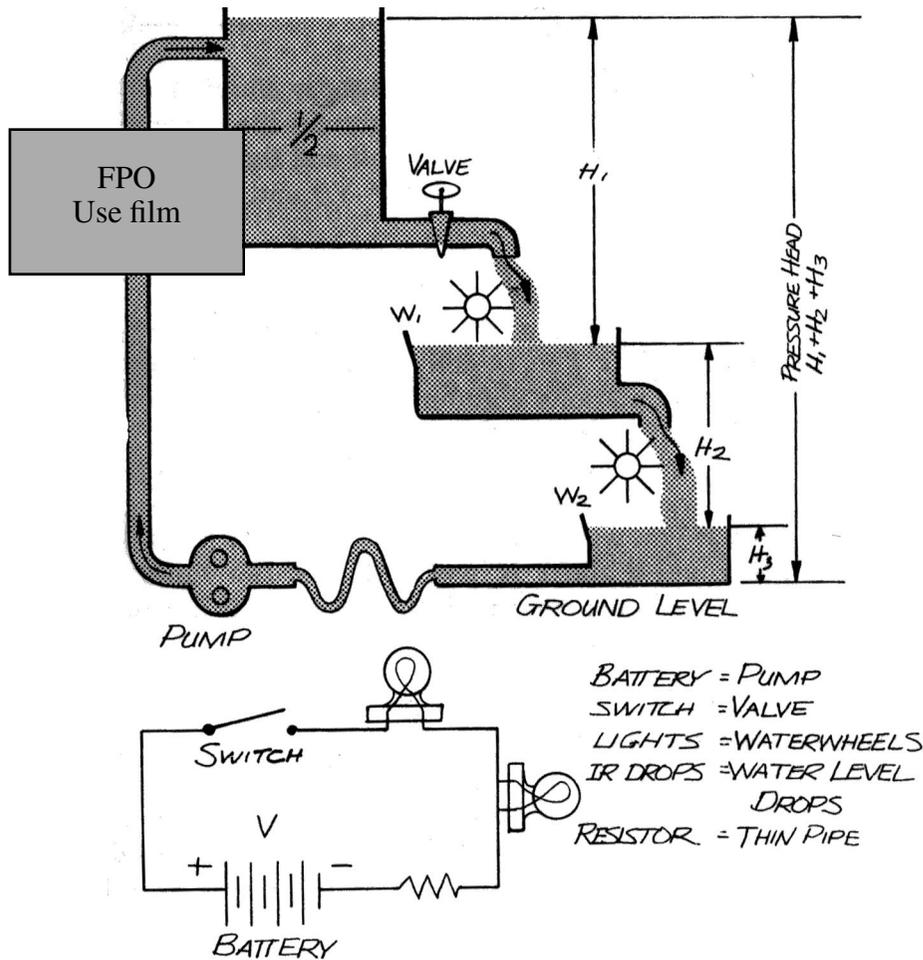
FPO
Use film

½

VALVE

W₁

W₂

H_1

H_2

H_3

PRESSURE HEAD
$H_1 + H_2 + H_3$

GROUND LEVEL

PUMP

SWITCH

V

+ BATTERY −

BATTERY = PUMP
SWITCH = VALVE
LIGHTS = WATERWHEELS
IR DROPS = WATER LEVEL
DROPS
RESISTOR = THIN PIPE

FIGURE 1-2

OHM'S LAW

In 1826 George Simon Ohm discovered the relationship between current, voltage, and resistance, which earned him his esteemed position

as one of the founders of electrical science. At the time of his discovery, he was not only ignored, but was even fired from his high school teaching job. Only later, after others realized the fundamental importance of Ohm's Law, was he rescued from poverty and awarded a professorship at the University of Munich.

Electric current is directly proportional to voltage and inversely proportional to resistance.

That simple statement is Ohm's Law. Utterly simple and yet profound. Increase the voltage in a circuit and the current increases. Increase the resistance in a circuit and the current decreases. In symbols it's $I = V/R$ and $R = V/I$ and $V = I \times R$.
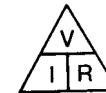
All three equations say the same thing, it just depends on which variable you need to find. This sketch of Ohm's Triangle makes it easy to do the calculations without having to remember all the formulas. The triangle has three boxes, V, I, and R. Just cover up the one you want to find, and do the arithmetic that is indicated. If you want V, cover it and I and R are next to each other; multiply. If you want I, cover it and V is over R; divide. If you want R, cover it and V is over I; divide. If a voltage of one volt is impressed on a circuit whose resistance is one ohm, then one amp of current will flow.

IR DROPS AND I²R HEAT

A few pages back when we were talking about the rule of electricity that says the EMF of the source is equal to the voltage drops around a circuit—known as *Kirchoff's Law* in physics books—we were refer-

ring to the third form of Ohm's equation, $V = I \times R$. In every item that offers resistance, the voltage drop across it is equal to the current through it times the resistance. We commonly refer to these effects as *IR drops*. The loss of energy by having it converted to heat in a resistance is always expressed in terms of power rather than energy. Remember that:

$$P = V \times I, \text{ and since } V = I \times R$$
$$\text{then } P = (I \times R) \times I \text{ or } P = I \times I \times R$$
$$\text{or } P = I^2R$$

Heat losses are always referred to as I^2R *losses*, spoken as "I squared R."

In our home kitchen, not likely our galley, we have several electric devices that we want to heat, such as a toaster and a lightbulb. The toaster will dissipate about 1,200 watts, the lightbulb 100. Let's see how they work on 120 volts (don't worry whether it is AC or DC) by calculating the current through each, and then the resistance of each.

TOASTER:
   $I = P/V = 1200$ watts/120 volts = 10 amps
   and $R = V/I = 120$ volts/10 amps = 12 ohms
LIGHTBULB:
   $I = P/V = 100$ watts/120 volts = 0.83 amps
   $R = V/I = 120$ volts/0.83 amps = 144 ohms

The resistance of the lightbulb is 12 times that of the toaster. What this means is that to toast bread you need lots of heat power. Since heat power is I^2R, you need a large current, which is obtained by using a lower resistance. In the lightbulb, only the tiny filament needs to be heated to give off light. Not much current is needed, so the resistance is considerably larger.

If all this is new to you, you may want to reread this section. It is important to lay these foundations early. We'll be calling on them again. But the math won't get any harder.