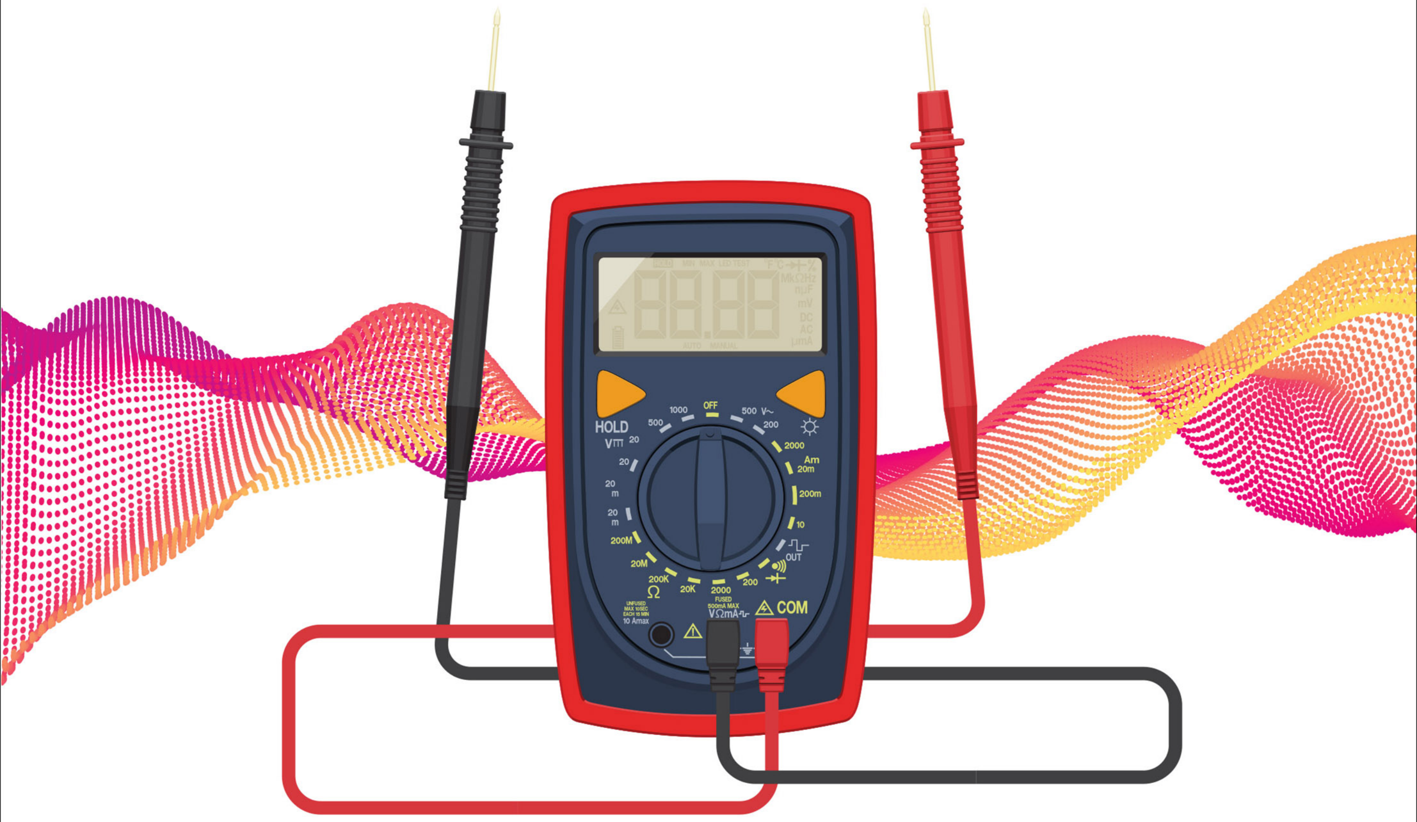
TEACH YOURSELF ELECTRICITY AND ELECTRONICS

SEVENTH EDITION



STAN GIBILISCO AND SIMON MONK

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Teach Yourself Electricity and Electronics

About the Authors

Stan Gibilisco (1955–2020) was a writer, electronics hobbyist, engineer, and HAM radio operator. Stan has authored several titles for the McGraw Hill *Demystified* and *Know-It-All* series, along with numerous other technical books and dozens of magazine articles. His *Encyclopedia of Electronics* (TAB Books, 1985) was cited by the American Library Association as one of the "best references of the 1980s." You can read about Stan on his Wikipedia page (https://en.m.wikipedia.org/wiki/Stan_Gibilisco).

Dr. Simon Monk has a degree in Cybernetics and Computer Science and a PhD in Software Engineering. Dr. Monk spent several years as an academic before he returned to industry, co-founding the mobile software company Momote Ltd. He has been an active electronics hobbyist since his early teens and as well as writing books, he designs products for MonkMakes Ltd, the company he started with his wife Linda. Dr. Monk is the author of numerous electronics books, including *Programming Arduino*, *Hacking Electronics*, and *Programming the Raspberry Pi*.

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Seventh Edition

Stan Gibilisco
Simon Monk

McGraw Hill

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In Memory of Stan

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Preface

This book will help you learn the fundamentals of electricity and electronics without taking a formal course. It can serve as a do-it-yourself study guide or as a classroom text. This seventh edition brings the book up to date with modern electronics. There is a much greater emphasis on the use of integrated circuits and practical electronic design.

If you need a mathematics or physics refresher, you can select from several of Stan Gibilisco's McGraw Hill books dedicated to those topics. If you want to bolster your mathematics knowledge base before you start this course, study *Algebra Know-It-All* and *Pre-Calculus Know-It-All*. On the practical side, check out *Electricity Experiments You Can Do at Home*.

If you get bitten by the microcontroller bug, then you'll find Simon Monk's *Programming Arduino: Getting Started with Sketches* and *Programming Arduino Next Steps: Going Further with Sketches* useful companions to this book.

In this edition, the chapter, section, and final exam quizzes are now provided as a separate download. You can find these at http://simonmonk.org/tyee7 or on the book's landing page on mhprofessional.com.

We welcome ideas and suggestions for future editions.

Simon Monk

Teach Yourself Electricity and Electronics

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1
PART
Direct Current

1
CHAPTER
Background Physics

YOU MUST UNDERSTAND SOME PHYSICS PRINCIPLES TO GRASP THE FUNDAMENTALS OF ELECTRICITY and electronics. In science, we can talk about *qualitative* things or *quantitative* things, that is, "what" versus "how much." For now, let's focus on "what" and worry about "how much" later!

Atoms

All matter consists of countless tiny particles in constant motion. These particles have density far greater than anything we ever see. The matter we encounter in our everyday lives contains mostly space, and almost no "real stuff." Matter seems continuous to us only because of the particles' submicroscopic size and incredible speed. Each chemical *element* has its own unique type of particle called its *atom*.

Atoms of different elements always differ! The slightest change in an atom can make a tremendous difference in its behavior. You can live by breathing pure *oxygen*, but you couldn't survive in an atmosphere comprising pure *nitrogen*. Oxygen will cause metal to corrode, but nitrogen will not. Wood will burn in an atmosphere of pure oxygen but won't even ignite in pure nitrogen. Nevertheless, both oxygen and nitrogen are *gases* at room temperature and pressure. Neither gas has any color or odor. These two substances differ because oxygen has eight *protons*, while nitrogen has only seven.

Nature provides countless situations in which a slight change in atomic structure makes a major difference in the way a sample of matter behaves. In some cases, we can force such changes on atoms (*hydrogen* into *helium*, for example, in a *nuclear fusion* reaction); in other cases, a minor change presents difficulties so great that people have never made them happen (*lead* into *gold*, for example).

Protons, Neutrons, and Atomic Numbers

The *nucleus*, or central part, of an atom gives an element its identity. An atomic nucleus contains two kinds of particles, the *proton* and the *neutron*, both of which have incredible density. A teaspoonful of protons or neutrons, packed tightly together, would weigh tons at the earth's surface. Protons and neutrons have nearly identical mass, but the proton has an electric charge while the neutron does not.

The simplest and most abundant element in the universe, hydrogen, has a nucleus containing one proton. Sometimes a nucleus of hydrogen has a neutron or two along with the proton, but not very often. The second most common element is helium. Usually, a helium atom has a nucleus with two protons and two neutrons. Inside the sun, nuclear fusion converts hydrogen into helium, generating the energy that makes the sun shine. The process is also responsible for the energy produced by a hydrogen bomb.

Every proton in the universe is identical to every other proton. Neutrons are all alike, too. The number of protons in an element's nucleus, the *atomic number,* gives that element its unique identity. With three protons in a nucleus we get *lithium*, a light metal solid at room temperature that reacts easily with gases, such as oxygen or chlorine. With four protons in the nucleus we get *beryllium*, also a light metal solid at room temperature. Add three more protons, however, and we have nitrogen, which is a gas at room temperature.

In general, as the number of protons in an element's nucleus increases, the number of neutrons also increases. Elements with high atomic numbers, such as lead, are therefore much more dense than elements with low atomic numbers, such as *carbon*. If you hold a lead shot in one hand and a similar-sized piece of charcoal in the other hand, you'll notice this difference.

Isotopes and Atomic Weights

For a given element, such as oxygen, the number of neutrons can vary. But no matter what the number of neutrons, the element keeps its identity, based on the atomic number. Differing numbers of neutrons result in various *isotopes* for a given element.

Each element has one particular isotope that occurs most often in nature, but all elements have multiple isotopes. Changing the number of neutrons in an element's nucleus results in a difference in the weight, and also a difference in the density, of the element. Chemists and physicists call hydrogen whose atoms contain a neutron or two in the nucleus (along with the lone proton) *heavy hydrogen* for good reason!

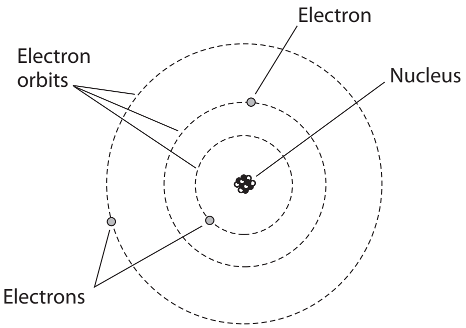
The *atomic weight* of an element approximately equals the sum of the number of protons and the number of neutrons in the nucleus. Common carbon has an atomic weight of 12. We call it *carbon 12* (symbolized C12). But a less-often-found isotope has an atomic weight very close to 14, so we call it *carbon 14* (symbolized C14).

Electrons

Surrounding the nucleus of an atom, we usually find a "swarm" of particles called *electrons*. An electron carries an electric charge that's *quantitatively* equal to, but *qualitatively* opposite from, the charge on a proton. Physicists arbitrarily call the electron charge *negative*, and the proton charge *positive*. The charge on a single electron or proton constitutes the smallest possible quantity of electric charge. All charge quantities, no matter how great, are theoretically whole-number multiples of this so-called *unit electric charge*.

One of the earliest ideas about the atom pictured the electrons embedded in the nucleus, like raisins in a cake. Later, scientists imagined the electrons as orbiting the nucleus, making the atom resemble a miniature solar system with the electrons as "planets," as shown in Fig. 1-1.

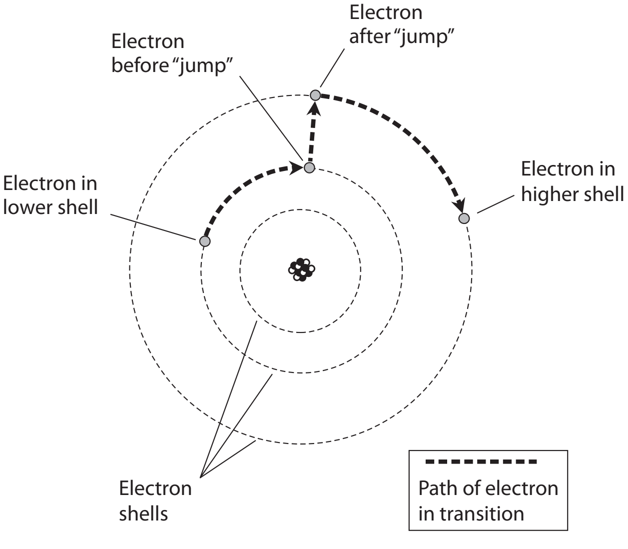
Today, we know that the electrons move so fast, with patterns of motion so complex, that we can't pinpoint any single electron at any given instant of time. We can, however, say that at any moment, a particular electron will just as likely "reside" inside a defined sphere as outside it. We call



1-1 An early model of the atom, developed around the year 1900. Electrostatic attraction holds the electrons in "orbits" around the nucleus.

an imaginary sphere of this sort, centered at the nucleus of an atom, an *electron shell*. These shells have specific, predictable radii. As a shell's radius increases, the amount of energy in an electron "residing in" the shell also increases. Electrons commonly "jump" from one shell to another within an atom, thereby gaining energy, as shown in Fig. 1-2. Electrons can also "fall" from one shell to another within an atom, thereby losing energy.

Electrons can move easily from one atom to another in some materials. In other substances, it is difficult to get electrons to move. But in any case, we can move electrons a lot more easily than we can move protons. Electricity almost always results, in some way, from the motion of electrons in a



1-2 Electrons move around the nucleus of an atom at defined levels, called shells, which correspond to discrete energy states. Here, an electron gains energy within an atom.

material. Electrons are much lighter than protons or neutrons. In fact, compared to the nucleus of an atom, the electrons weigh practically nothing.

Quite often, the number of electrons in an atom equals the number of protons. The negative charges, therefore, exactly cancel out the positive ones, and we get an *electrically neutral* atom, where "neutral" means "having a net charge of zero." Under some conditions, an excess or shortage of electrons can occur. High levels of radiant energy, extreme heat, or the presence of an electric field (discussed later) can "knock" or "throw" electrons loose from atoms, upsetting the balance.

Ions

If an atom has more or fewer electrons than protons, then the atom carries an electrical charge. A shortage of electrons produces a positive charge; an excess of electrons produces a negative charge. The element's identity remains the same no matter how great the excess or shortage of electrons. In the extreme, all the electrons might leave the influence of an atom, leaving only the nucleus; but even then, we still have the same element. We call an electrically charged atom an *ion*. When a substance contains many ions, we say that the substance is *ionized*.

The gases in the earth's atmosphere become ionized at high altitudes, especially during the daylight hours. Radiation from the sun, as well as a constant barrage of high-speed subatomic particles from space, strips electrons from the nuclei. The ionized gases concentrate at various altitudes, sometimes returning signals from surface-based radio transmitters to the earth, allowing for long-distance broadcasting and communication.

An ionized material can conduct electricity fairly well even if, under normal conditions, it conducts poorly or not at all. Ionized air allows a *lightning stroke* (a rapid electrical *discharge* that causes a visible flash) hundreds or even thousands of meters long to occur, for example. The ionization, caused by a powerful electric field, takes place along a jagged, narrow path called the *channel*. During the stroke, the atomic nuclei quickly attract stray electrons back, and the air returns to its electrically neutral, normal state.

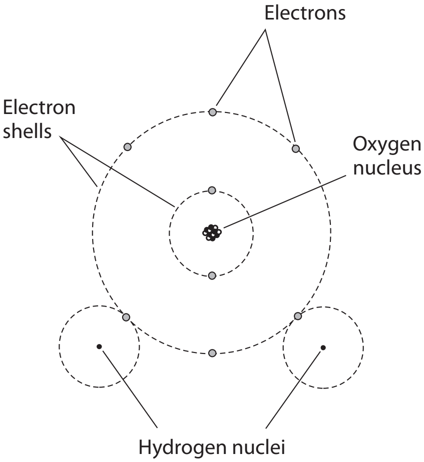
An element can exist as an ion and also as an isotope different from the most common isotope. For example, an atom of carbon might have eight neutrons rather than the usual six (so it's C14 rather than C12), and it might have been stripped of an electron, giving it a positive unit electric charge (so it's a positive ion). Physicists and chemists call a positive ion a *cation* (pronounced "cat-eye-on") and a negative ion an *anion* (pronounced "an-eye-on").

Compounds

Atoms of two or more different elements can join together by sharing electrons, forming a chemical *compound*. One of the most common compounds is water, the result of two hydrogen atoms joining with an atom of oxygen. As you can imagine, many chemical compounds occur in nature, and we can create many more in chemical laboratories.

A compound differs from a simple mixture of elements. If we mix hydrogen gas with oxygen gas, we get a colorless, odorless gas. But a spark or flame will cause the atoms to combine in a chemical reaction to give us the compound we call *water*, liberating light and heat energy. Under ideal conditions, a violent explosion will occur as the atoms merge almost instantly, producing a "hybrid" particle, as shown in Fig. 1-3.

Compounds often, but not always, have properties that drastically differ from either (or any) of the elements that make them up. At room temperature and pressure, both hydrogen and oxygen are gases. But under the same conditions, water exists mainly in liquid form. If the temperature falls



1-3 Two hydrogen atoms readily share electrons with a single atom of oxygen.

enough, water turns solid at standard pressure. If it gets hot enough, water becomes a gas, odorless and colorless, just like hydrogen or oxygen.

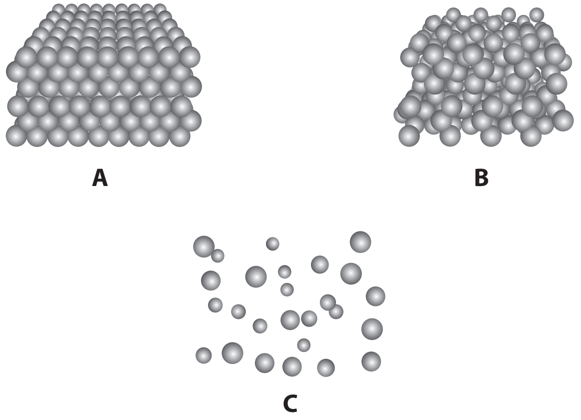
Another common example of a compound is rust, which forms when *iron* joins with oxygen. While iron appears to us as a dull gray solid and oxygen appears as a gas, rust shows up as a red-brown powder, completely unlike either iron or oxygen. The chemical reaction that produces rust requires a lot more time than the reaction that produces water.

Molecules

When atoms of elements join in groups of two or more, we call the resulting particles *molecules*. Figure 1-3 portrays a molecule of water. Oxygen atoms in the earth's atmosphere usually pair up to form molecules, so you'll sometimes see oxygen symbolized as O_2. The "O" represents oxygen, and the subscript 2 indicates two atoms per molecule. We symbolize water by writing H_2O to show that each molecule contains two atoms of hydrogen and one atom of oxygen.

Sometimes oxygen atoms exist all by themselves; then, we denote the basic particle as O, indicating a lone atom. Sometimes, three atoms of oxygen "stick" together to produce a molecule of *ozone*, a gas that has received attention in environmental news. We symbolize ozone by writing O_3. When an element occurs as single atoms, we call the substance *monatomic*. When an element occurs as two-atom molecules, we call the substance *diatomic*. When an element occurs as three-atom molecules, we call the substance *triatomic*.

Whether we find it in solid, liquid, or gaseous form, all matter consists of molecules or atoms that constantly move. As we increase the temperature, the particles in any given medium move faster. In a solid, we find molecules interlocked in a rigid matrix so they can't move much (Fig. 1-4A), although they vibrate continuously. In a liquid, more space exists between the molecules (Fig. 1-4B), allowing them to slide around. In a gas, still more space separates the molecules, so they can fly freely (Fig. 1-4C), sometimes crashing into each other.



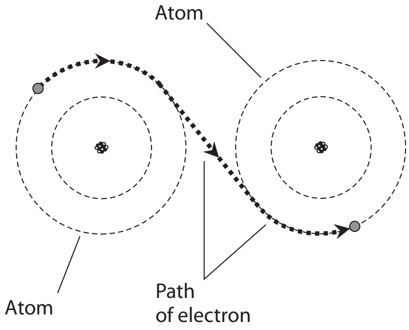
1-4 Simplified renditions of molecular arrangements in a solid (A), a liquid (B), and a gas (C).

Conductors

We define an electrical *conductor* as a substance in which the electrons can move with ease. The best known conductor at room temperature is pure elemental *silver*. *Copper* and *aluminum* also conduct electricity well at room temperature. Various other metals constitute fair to good conductors. In most electrical circuits and systems, we find copper or aluminum wire.

Some liquids conduct electricity quite well. *Mercury* provides a good example. Salt water conducts fairly well, but it depends on the concentration of dissolved salt. Gases or mixtures of gases, such as air, usually fail to conduct electricity because the large distances between the atoms or molecules prevent the free exchange of electrons. If a gas becomes ionized, however, it can conduct fairly well.

In an electrical conductor, the electrons "jump" from atom to atom (Fig. 1-5), predominantly from negatively charged locations toward positively charged locations. In a typical electrical circuit, many trillions, quadrillions, or quintillions of electrons pass a given point every second.



1-5 In an electrical conductor, some electrons pass easily from atom to atom.

Insulators

An electrical *insulator* prevents electron movement among atoms, except occasionally in tiny amounts. Most gases make good electrical insulators. Glass, dry wood, dry paper, and plastics also insulate well. Pure water normally insulates, although some dissolved solids can cause it to conduct. Certain metal oxides can function as good insulators, even if the metal in its pure form makes a good conductor.

Sometimes, you'll hear an insulating material called a *dielectric*. This term arises from the fact that a sample of the substance can keep electrical charges apart to form an *electric dipole*, preventing the flow of electrons that would otherwise equalize the charge difference. We encounter dielectrics in specialized components, such as *capacitors*, through which electrons *should not* directly travel.

Engineers commonly use porcelain or glass in electrical systems. These devices, called insulators in the passive rather than the active sense, are manufactured in various shapes and sizes for different applications. You can see them on utility lines that carry high *voltage*. The insulators hold the wire up without risking a *short circuit* with a metal tower or a *bleedoff* (slow discharge) through a salt-water-soaked wooden pole.

If we try hard enough, we can force almost any electrical insulator to let electrons move by forcing ionization to occur. When electrons are stripped away from their atoms, they can roam more or less freely. Sometimes a normally insulating material gets charred, or melts down, or gets perforated by a spark. Then it loses its insulating properties, and electrons can move through it.

Resistors

Some substances, such as carbon, allow electrons to move among atoms *fairly* well. We can modify the conductivity of such materials by adding impurities such as clay to a carbon paste, or by winding a long, thin strand of the material into a coil. When we manufacture a component with the intent of giving it a specific amount of conductivity, we call it a *resistor*. These components allow us to limit or control the rate of electron flow in a device or system. As the conductivity improves, the *resistance* decreases. As the conductivity goes down, the resistance goes up. Conductivity and resistance vary in *inverse proportion*.

Engineers express resistance in units called *ohms*. The higher the resistance in ohms, the more opposition a substance offers to the movement of electrons. For wires, the resistance is sometimes specified in terms of *ohms per unit length* (foot, meter, kilometer, or mile). In an electrical system, engineers strive to minimize the resistance (or *ohmic value*) because resistance converts electricity into heat, reducing the *efficiency* that the engineers want and increasing the *loss* that they don't want.

Semiconductors

In a *semiconductor*, electrons flow easily under some conditions, and with difficulty under other conditions. In their pure form, some semiconductors carry electrons almost as easily as good conductors, while other semiconductors conduct almost as poorly as insulators. But semiconductors differ fundamentally from plain conductors, insulators, or resistors. In the manufacture of a semiconductor device, chemists treat the materials so that they conduct well some of the time, and poorly some of the time—and we can control the conductivity by altering the conditions. We find semiconductors in *diodes*, *transistors*, and *integrated circuits*.