CHAPTER 12

Electronics

Electric currents and magnetized metals can do more than simply power lightbulbs or attach notes to refrigerators. They can also represent many different things, from sounds to video images to computerized information. Moreover, they can be used to manipulate that information in remarkable ways and at astonishing speeds. In this chapter, we'll see how electricity and magnetism have given rise to the field of electronics.

Electronic devices are tools that use electric currents to perform sophisticated tasks. They first appeared in the early twentieth century with the development of vacuum tubes and have been maturing ever since. Advances in electronics have frequently followed advances in quantum and solid-state physics, so it was hardly surprising that research into the physics of semiconductors should lead to interesting electronics. However, the invention of the semiconductor transistor shortly after World War II started a revolution in electronics so profound that no one could have anticipated it. Advanced jointly by physicists and engineers, electronic devices have gradually become so inexpensive and so effective that they now permeate every part of modern society.

EXPERIMENT: Building an Electronic Kit

You've been using electronic devices all your life, so merely using them some more is unlikely to add to your insight. To get a real feel for how electronic devices work, your best bet is to build one!

Courtesy Lou Bloomfield

There are many simple kits available over the Internet, easily found by searching for "electronic kits" or "solder practice kits." Soldering is the technique of connecting electronic components with a soft metal that melts easily when heated by a soldering iron. Snap-together experiment kits are also available, but they're more expensive and less like real electronic devices.

Look for a kit that contains some basic electronic components: resistors, capacitors, diodes, and transistors, and be sure to get or borrow a soldering iron and some solder. If you can afford it, buy a simple electronic multimeter to check the behavior of your kit. Even when you're done with the kit, that meter should come in handy. It is to the electrician or electronics technician what a ruler, square, and level are to a carpenter or surveyor.

Find a safe, well-lighted work space and read the kit instructions carefully before you begin. You'll be inserting the wire ends or "leads" of the various electronic components into holes in a printed circuit board—an insulating card bearing photographically printed metal strips. Those strips connect the kit's components, although you will have to complete the connections using solder and your soldering iron. Be careful not to burn yourself as you melt the solder into place. Make sure that the solder *wets* each metal surface—that it spreads out like water on paper towel rather than beading up like water on waxed paper.

As you assemble your kit, note the differences between the components. Some of the components must be inserted in the right orientation. Why is that? Those same directional components are usually heat-sensitive and mustn't be warmed too long with the soldering iron. What might elevated temperatures do to those components?

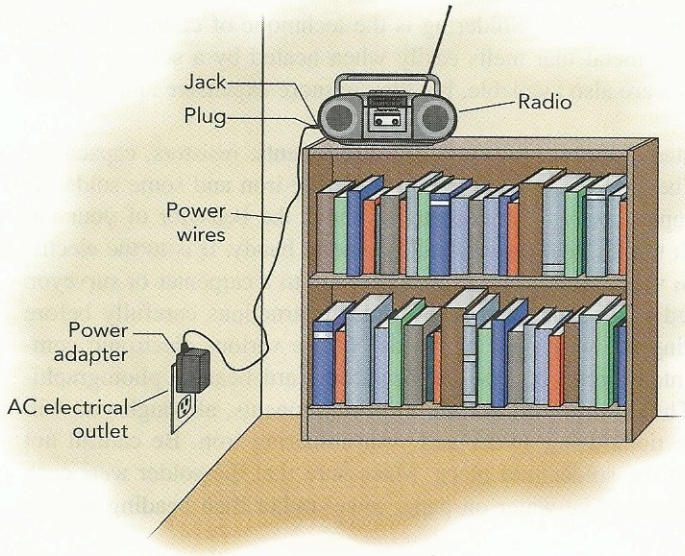
As you build your device, think about how current will flow through its various components and what the voltages will be at various points in the device. How might those currents and voltages change with time? From the instructions and your intuition, try to determine what role each component plays in the overall device.

When the kit is complete, turn it on and watch it work (hopefully). If you have a multimeter, select the "DC Voltage" setting and measure the voltages at various points in the device. To do that, you'll have to give the meter a reference for 0 V by connecting its black wire to the battery's negative terminal and then touch the meter's red wire to the spot whose voltage you wish to measure. With guidance from the kit's instructions and some careful thought, you should be able to understand how electric currents are flowing through the components and making interesting things happen.

Chapter Itinerary

To understand the remarkable properties of electronic devices, we'll examine two of them: (1) *power adapters* and (2) *audio players*. In *power adapters*, we'll look at how these simple devices use power obtained from the relatively high-voltage alternating current of electrical outlets to provide the relatively low-voltage direct current required by most electronic equipment. In *audio players*, we'll see how a small assortment of basic electronic components are brought together to build a computer and an audio amplifier, and how those two devices have been merged together into a single unit so that you can listen to thousands of songs as you lounge on the beach. For additional preview information, turn ahead to the Chapter Summary at the end of the chapter.

Although this brief survey can't go beyond the most basic issues in electronics, it should provide a good foundation on which to build. Once you understand how a few important electronic components work, it's not so hard to see how to combine them in ways that no one else has ever imagined. Like building blocks that control the movements of charged particles, electronic components can be put together to do almost anything.



SECTION 12.1 Power Adapters

Virtually every electronic device you buy comes with its own power adapter, a small black cube or brick that either plugs directly into an electrical outlet or has a cord that does. These adapters obtain power from the century-old electrical grid and prepare it for this week's gadgets. Power adapters range widely in the voltages and currents they supply, the degree to which their voltages are smoothed and regulated, and even the connectors through which they deliver their power. The result is dozens of adapters that are rarely interchangeable and, consistent with Murphy's law, the adapter you need is always the one that fell behind the bookshelf.

Despite their differences, however, these power adapters all perform essentially the same conceptual task: they take relatively high voltage alternating current and use its power to prepare relatively low voltage direct current. They do this conversion efficiently, inexpensively, and with a high degree of reliability. In this section, we'll see how simple power adapters perform that conversion.

Questions to Think About: *Why can't most electronic devices operate from alternating current? Why do those devices need direct current that's supplied at a certain voltage? What is the relationship between the batteries a device uses and the voltage of its power adapter? When the voltage and current of an electrical outlet reach zero during a reversal of its alternating current, what might happen to the output of the power adapter? What might the adapter do to endure that reversal?*

Experiments to Do: *Unless you live in a log cabin, you probably have several power adapters sitting in your closet or under your bed. Take a look at those adapters. The simplest ones will be cubes that plug directly into electrical outlets. Examine them to see that each provides a specific DC voltage with a specified maximum current. Furthermore,*

each expects a narrow range of input voltages, such as 120-V AC in the United States or 230-V AC in Europe. What would happen if you plugged one of these adapters into the wrong electrical outlet? (Warning: Don't try it! A 120-V AC adapter will destroy both itself and the attached device when plugged into a 230-V AC outlet, while a 230-V AC adapter will survive but will fail to operate its device properly.)

Adapters that resemble bricks with power cords are usually more complicated than the wall-cube adapters. Used with computers and other more sophisticated devices, these bricks generally regulate their output voltages carefully. Furthermore, they can typically handle a wider range of input voltages, such as 100-V AC to 240-V AC. What makes accepting such a range of input voltages so challenging?

Some of your adapters may have lights to indicate when they're working. Plug these adapters in and then unplug them. Do their lights go out immediately? If not, why not?

Finally, if you have a cube adapter that you no longer need, carefully open it up. Be safe: unplug it first and don't cut yourself. Inside it, you'll find a transformer and several semiconductor devices called diodes. You may also find a storage device called a capacitor. Together, these components can prepare low-voltage DC from high-voltage AC—and that's what this section is all about.

Producing DC Power from AC Power

Although electrical devices such as toasters and incandescent lightbulbs can operate from either AC or DC power, most electronic devices require DC power. There are two reasons for their pickiness. First, they contain sophisticated electronic components that are sensitive to the direction of current flow and won't operate properly if that current is reversed. Second, electronic devices typically need a continuous supply of power and can't tolerate the brief moments of powerlessness that occur when alternating current is reversing.

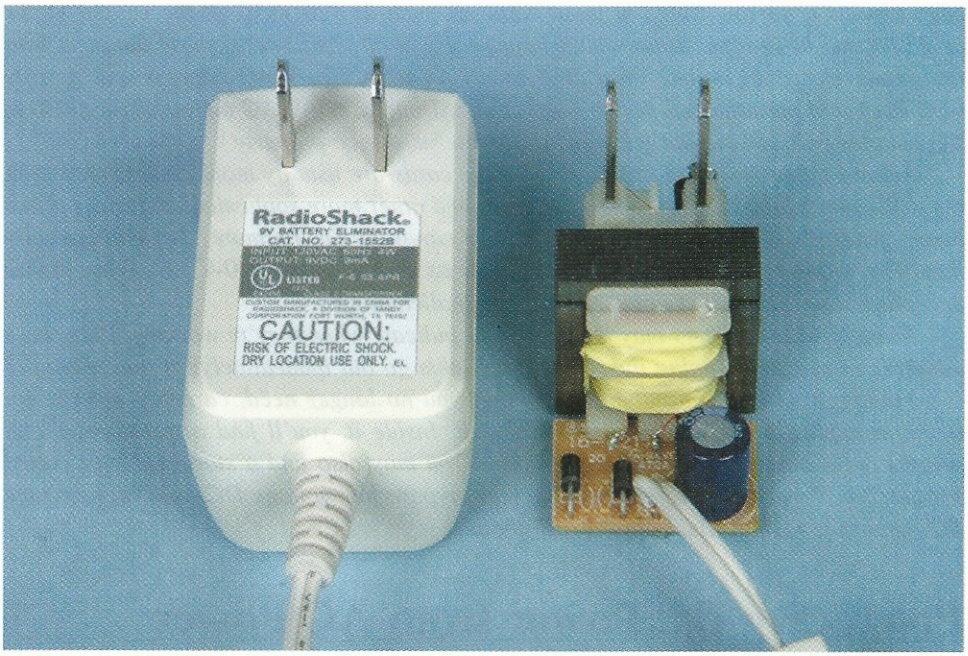
Addicted as they are to direct current, electronic devices operate beautifully on batteries. Of course, those batteries must be installed in the right direction or they'll act to push current the wrong way. But batteries and electronics are practically made for each other.

Unfortunately, batteries eventually run out of stored energy and must be replaced or recharged. Also, some electronic devices are so power-hungry that operating them on batteries would cost a fortune. Unless you're an heiress or the nephew of a battery manufacturer, you often need a cheaper, more practical source of DC power. You need a power adapter.

A power adapter's task is simple: it uses AC power from an electrical outlet to provide DC power to an electronic device. More specifically, it delivers current to the electronic device through a positive power wire and receives that current back through a negative power wire. The adapter maintains a specified average voltage rise from the negative wire to the positive wire, as though the adapter were a battery.

The steadiness of an adapter's voltage rise depends on its sophistication. Some adapters let their voltage rises fluctuate with the AC cycle, while others use complicated electronics to regulate their voltage rises precisely. Intermediate between those two extremes are adapters that use simple electronics to smooth out most of the fluctuations due to the AC cycle but make no further attempt to regulate their voltages. In this section, we'll examine these intermediate power adapters.

To be specific, we'll examine the components in a 9-V DC power adapter (Fig. 12.1.1) that operates from 120-V AC power and supplies power to an ordinary radio. The radio needs approximately 9-V power: a much larger voltage drop would damage its components



Courtesy Lou Bloomfield

Fig. 12.1.1 These two power adapters use 120-V AC power from an electrical outlet to produce 9-V DC power for a radio. The adapter on the right has been removed from its plastic shell to reveal a transformer (*top*), two black diodes (*lower left*), and a cylindrical capacitor (*lower right*).

and a much smaller voltage drop prevent it from functioning. Nonetheless, the radio can tolerate small variations in the voltage drop provided to it.

Apart from wires, this adapter contains only a few components: a transformer, four diodes, and a capacitor. To understand this power adapter, we need only examine those components and how they interact. Since we studied transformers in Section 11.2, we already have a head start.

When you plug the transformer into an electrical outlet, its primary coil forms a circuit with the power company and an alternating current flows through it. The primary coil has 13⅓ times as many turns as the secondary coil, so the secondary coil provides an induced emf of 9-V AC.

The adapter then converts 9-V AC into 9-V DC; it uses 9-V alternating current from the transformer to provide 9-V direct current to the radio. That simple-sounding conversion will keep us busy for the remainder of this section. In large part, that's because it involves two devices that we haven't encountered before: diodes and capacitors.

Diodes are one-way conductors of electric current. Unlike a wire, which carries current equally well in either direction (Fig. 12.1.2*a*), a diode allows current to flow through it only in one direction (Fig. 12.1.2*b*). It acts as a conductor when current tries to flow

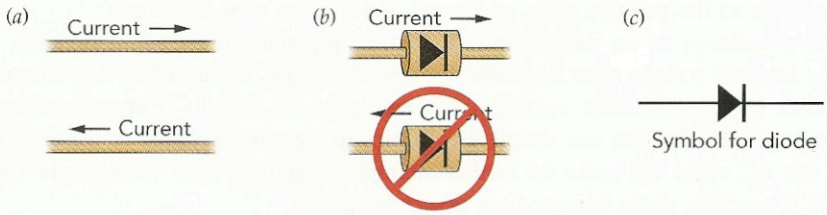


Fig. 12.1.2 (*a*) A wire can carry current in either direction. (*b*) A diode can carry current only in the direction shown symbolically by its arrow. (*c*) In a schematic diagram of an electronic device, the diode is represented by an arrow and bar.

in the allowed direction and as an insulator when current tries to flow in the forbidden direction. This switching behavior is what the power adapter uses to obtain direct current from alternating current.

Capacitors are devices that store separated electric charges. By accumulating positive charge on one side and negative charge on the other side, a capacitor stores both charge and energy. That storage helps the adapter steady its voltage rise and endure the moments when the reversing alternating current provides no power to the adapter.

Check Your Understanding #1: Safety First

A radio operates from a power adapter that's plugged into an electrical outlet. What fraction of the current flowing through the radio also flows through the electrical outlet?

Answer: None of the current flowing through the radio also flow, through the outlet.

Why: Current from the electrical outlet flows through the primary coil of the adapter's transformer and then returns to the electrical outlet. Current from the secondary coil of that transformer flows through the radio and then returns to the secondary coil. These two circuits, the primary circuit with the power outlet and the secondary circuit with the radio, are electrically isolated: they can exchange power but not charge. The isolation between those two circuits provides a measure of electrical safety to the user of the radio and the power adapter.

A Few Words about Quantum Physics

Since a diode is sensitive to the direction of current flow, it can't be symmetric. It must have two distinct and different ends. To understand those two ends and how they differ, we need to examine the materials from which they're both made. We need to examine semiconductors.

Semiconductors are materials with properties intermediate between those of electrical conductors and those of electrical insulators. While charge is *always* mobile in conductors and *almost never* mobile in insulators, charge is *sometimes* mobile in semiconductors. In general, a semiconductor acts like an insulator when it is cold, pure, and in the dark, and it acts like a conductor when it is hot, impure, or exposed to light. Semiconductors are so important to diodes and to most of modern electronics that we'll spend the next several pages learning how charge moves through them. We'll begin by discussing quantum physics, which has immense influence over the tiny particles from which semiconductors are built.

As quantum physics gradually revealed itself to the scientists of the early twentieth century, they found the experience both exhilarating and disorienting. Prior to that era, the physical world seemed to divide neatly into particles and waves: scientists viewed an electron only as a particle and light only as a wave. However, one of the most basic observations of quantum physics, and the one most relevant to our present topic, is that everything has both particle and wave characteristics. Put simply, everything begins and ends as a particle, but travels as a wave.

For an electron, the quantum surprise is that it travels as a wave. For light, the quantum surprise is that it is emitted and absorbed as a particle. Called the **wave–particle duality**, this observation that everything in nature has both particle and wave characteristics has left few areas of physics unaffected. But although quantum physics is now a basic and essential part of nearly all modern physics research, its effects are subtle and

often nonintuitive. They are most apparent in the microscopic world and are visible to us only indirectly. No wonder they seem so strange.

We'll encounter quantum physics and its effects several times in the next few chapters. It figures prominently in the electronic properties of semiconductors, in the light emitted by atoms and lasers, and in the radioactive decays that release nuclear energy. Our examination of semiconductors will acquaint us with the wave nature of electrons and show how the wave phenomena that we studied in Chapter 9 apply to quantum physics. Our exploration of light from atoms and lasers will acquaint us with the particle nature of light and how the collision effects we explored in Chapters 1–3 apply to quantum physics. In our examination of radioactivity, we'll uncover particle and wave effects that we would not even have anticipated without quantum physics. With each encounter, we'll take a small bite of the quantum apple—looking at how quantum effects manifest themselves in our everyday world.

Check Your Understanding #2: Wavy Atoms

Do atoms ever exhibit wave properties?

Answer: They certainly do.

Why: Like everything else in nature, atoms have both particle and wave properties. Atoms travel as waves and have recently been shown to exhibit many of the wave effects we studied in Chapter 9, including refraction, reflection, and interference.

Electrons in Solids

We learned in Chapter 10 that metals conduct electricity because they contain mobile electrons and that insulators don't conduct electricity because none of their electrons are mobile. Now it's time to see what controls electron mobility. As you might guess, the explanation lies in quantum physics.

In a nonquantum world, an electron in a solid would travel only as a particle and it would be able to move at any speed along any path. However, ours is a quantum world and the electron does not travel as a particle at all; it travels as a wave. Like the waves on a violin string, drumhead, or basin of water, the electron waves in a solid have limited possibilities.

In Chapter 9, we observed that the most basic mechanical waves on a limited object are all standing waves—waves that effectively oscillate in place. This rule also applies to quantum waves. The electrons in a solid are best understood as standing waves in that solid. Each electron wave extends across part or all of the solid and has such wave characteristics as wavelength and frequency. Unlike a vibrating string or drumhead, the electron is a three-dimensional wave and its oscillation is internal—but it's still a wave.

This wave character has profound effects on the electronic structure of solids. Most significantly, it limits what electrons can do in those solids. We saw in Chapter 9 that a violin string's one-dimensional standing waves consist only of its fundamental mode (Fig. 9.2.3) and its harmonic modes (Fig 9.2.4) and that a drumhead's two-dimensional standing waves consist only of its fundamental mode and overtones (Fig. 9.2.9). Similarly, a solid's three-dimensional electron standing waves consist only of a fundamental mode and overtones. Also, while there are a great many overtone modes available, their possibilities are nonetheless limited.

The electron standing waves in solids are often called **levels**—a recognition that each standing wave has an amount or "level" of energy associated with it. The electron standing waves in atoms, another group of limited systems in which electrons exist as standing waves, are called orbitals—a nod to the orbiting nature of an atom's electrons. We'll see when we examine discharge lamps in Section 14.2 that each atom's limited orbital choices determine the colors of light it can emit or absorb. We'll see in the present section that a solid's limited level choices determine its electrical conductivity.

Another remarkable observation of quantum physics is that every indistinguishable electron must have its own level or orbital, its own unique quantum wave. This law is called the **Pauli exclusion principle**, after its discoverer, Wolfgang Pauli ■. The principle applies to a whole class of subatomic particles, the **Fermi particles**, that includes all of the basic constituents of matter: electrons, protons, and neutrons. For reasons that lie deep in an area of physics known as quantum field theory, two indistinguishable Fermi particles can never be in the same quantum wave.

■ Austrian physicist Wolfgang Pauli (1900–1958) rose to fame at 21 by writing an article on relativity that impressed even Einstein. He went on to discover the exclusion principle, a fundamental part of quantum theory. He was renowned for his intensely critical attitude toward new ideas, considering them all "rubbish" until convinced otherwise. Pauli was also quite interested in psychology, corresponding with Carl Gustav Jung and writing a number of articles on the subject.

The Pauli Exclusion Principle
No two indistinguishable Fermi particles ever occupy the same quantum wave.

However, a peculiar property of electrons allows two of them to share an orbital or level. Electrons have two possible internal states, usually called spin-up and spin-down. Because a spin-up electron is distinguishable from a spin-down electron, one spin-up electron and one spin-down electron can share a single orbital or level. However, two electrons is the absolute maximum allowed by quantum physics and the Pauli exclusion principle.

Despite being a wave, an electron in a level has a specific total energy—the sum of its kinetic and potential energies. That energy, which depends on the shape and structure of the electron wave, also determines the wave's oscillation frequency. According to quantum physics, the electron's total energy and the oscillation frequency of its wave are exactly proportional to one another; a low-energy electron oscillates slowly while a high-energy electron oscillates quickly. We'll return to this observation in Chapter 14, but for now we'll note that each level, each quantum standing wave in the solid, has a specific frequency and energy. The solid's fundamental standing wave has the lowest frequency and energy, while the overtone waves have progressively higher frequencies and energies.

Physicists have come to view these standing waves as abstract placeholders, independent of the electrons that may or may not exhibit them at a given moment. The levels are then analogous to seats in a theater, each of which may or may not be occupied right now. Instead of saying that the *electron* is experiencing a particular standing wave or level, we say that the *level* is occupied by an electron. In this reversed perspective, the level plays the more important role. For the rest of this section, we'll view a solid in this manner; we'll think in terms of the levels it has available and whether or not those levels are occupied by electrons.

A solid contains an enormous number of electrons, and there are always plenty of levels around to accommodate those electrons. But which levels do they occupy?

At sufficiently low temperature, electrons occupy those levels that have the least energy. For thermodynamic reasons, the electrons settle into the lowest energy levels available, two electrons per level. By the time all the electrons have been accommodated, they fill the levels up to a certain maximum energy. Halfway between the highest filled level and lowest unfilled level is the **Fermi level**—a hypothetical level that defines the

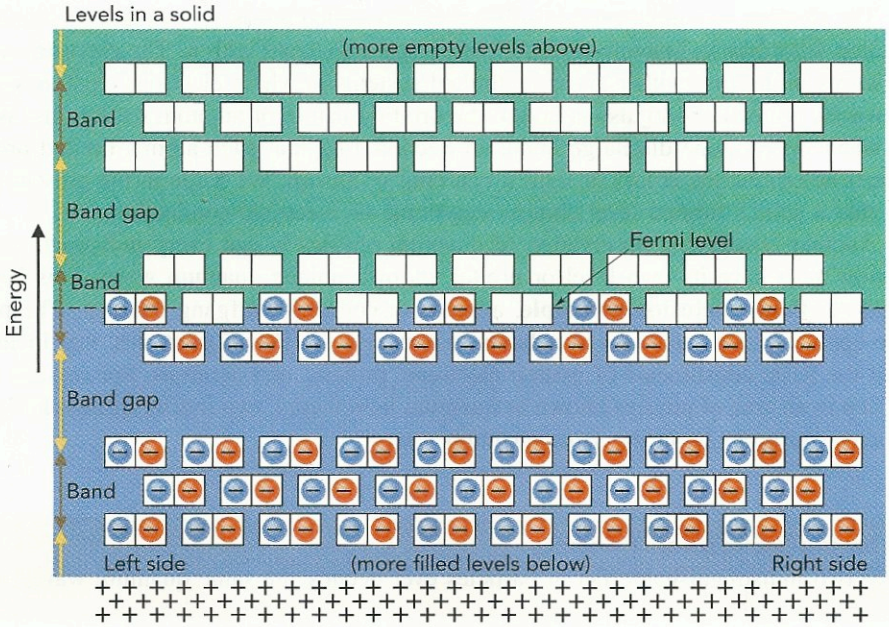


Fig. 12.1.3 The levels in a solid are grouped together in bands and filled from the lowest energy level up to the Fermi level. Each level can hold at most two electrons: one spin-up electron (*blue*) and one spin-down electron (*red*). The positive charges shown at the bottom are the nuclei of atoms that make up this electrically neutral solid.

top of this *Fermi sea* of electrons. The energy an electron would have in that hypothetical level is called the **Fermi energy**.

Our theater analogy can again provide insight into this level-filling process. It is analogous to what happens at a popular show: the seats fill from the orchestra level on up—everyone wants to sit in the lowest (and closest) seat. When the show starts, people have filled all the seats up to a certain highest seat. Halfway between that last filled seat and the next unfilled seat is the hypothetical Fermi seat.

If we represent the levels graphically by boxes and arrange them vertically according to energy (Fig. 12.1.3), then levels (boxes) below the Fermi level contain two electrons each, while those above the Fermi level are empty. Although thermal energy complicates this picture somewhat by shifting electrons about near the Fermi level, we can ignore that detail near room temperature or below.

Since levels are standing waves, they don't have sharply defined locations in space. However, we can safely imagine that each level places its electrons near a particular location in the solid, as shown in Fig. 12.1.3. Although this picture is somewhat oversimplified, it's accurate enough to illustrate much of the physics of charge motion in materials.

Of course, electrons aren't the only charged particles in a solid. The atoms also have positively charged nuclei, but those nuclei are essentially immobile and rarely participate in the flow of electricity. Instead, they form a uniform background of positive charge, shown schematically as pluses (+) at the bottom of Fig. 12.1.3, so that the object is roughly neutral throughout.

Check Your Understanding #3: Taking It to a Higher Level

If you add one extra electron to an otherwise neutral metal ball, into which level will that electron go?

Answer: The electron will go into the lowest energy empty level, the one just above the Fermi level.

Why: Since each electron goes into the lowest energy level that's available, this new electron will fill the level just above the Fermi level. Actually, if the metal ball had an odd number of electrons, then the Fermi level only contained one electron. In that case, the new electron will fill the other opening in the Fermi level.

Metals, Insulators, and Semiconductors

The levels in a solid occur in groups called **bands**. Each band corresponds to standing waves with a particular type of structure. Since the levels in a band involve similar waves, they also involve similar energies. Between these bands of levels there are sometimes **band gaps**—ranges of energy in which no levels exist. The solid does not and cannot contain electrons with energies that lie within a band gap.

Bands and band gaps are what distinguish metals, insulators, and semiconductors. When the Fermi level is located in a band gap, it can prevent the electrons in a solid from responding to outside forces. To see how that happens, let's examine first a metal and then an insulator.

In a **metal**, the Fermi level lies in the middle of a band (Fig. 12.1.4). Because the band's empty levels are just above its filled levels, very little energy is needed to shift electrons from filled levels to empty levels. This feature allows the metal to conduct electricity. When you put positive charges on the metal's left side and negative charges on its right, its electrons experience leftward electrostatic forces and begin to move left. They move by shifting from filled levels to empty levels (Fig. 12.1.4), obtaining the energy needed to reach those empty levels from the work done on them by the electrostatic forces. Overall, electrons enter the metal from its right and leave from its left, so the metal conducts electricity!

In our theater analogy, a metal is a theater in which only about half the ground-floor seats are filled. If you ask people in the theater to begin shifting left, those near the top of the occupied seats can shift about easily. Each finds an empty seat nearby on the left and moves over. New people are then able to enter the theater from the right while others leave the theater from the left. This "metal" theater would be "conducting" people.

Unlike the situation in a metal, the Fermi level of an **insulator** lies in the middle of a band gap, between the top of one band and the bottom of another band (Fig. 12.1.5). With no easily accessible empty levels available, a great deal of energy is required to shift electrons from filled levels to empty levels. When you put positive charges on the insulator's left side and negative charges on its right, its electrons experience leftward electrostatic forces but are unable to move. To shift into one of the empty levels in the upper band, an electron in the lower band would need more energy than it can get from the electrostatic forces. Since no net charge flows through the insulator, it doesn't conduct electricity!

In our theater analogy, an insulator is a theater in which all the ground-floor seats are full and the balcony seats are empty. When you ask people in this theater to begin shifting left, they can't do it. All of the ground-floor seats to the left are filled, and they

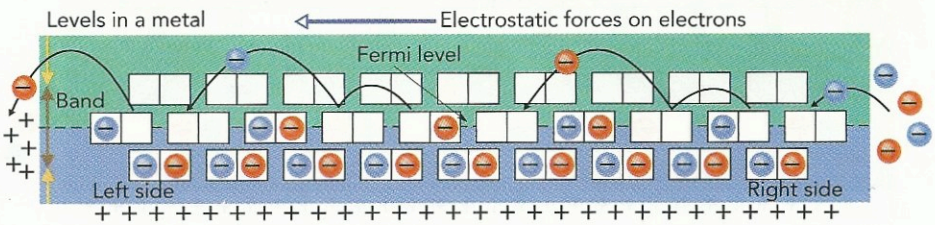


Fig. 12.1.4 In a metal, the Fermi level lies in the middle of a band. When you put electrons to the metal's right and positive charges to the metal's left, electrons shift leftward through the metal with the help of the empty levels. Since there is a net flow of charges through the metal, it is conducting electricity.

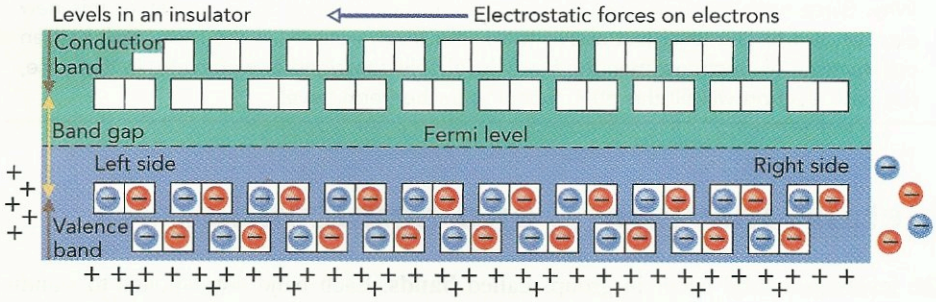


Fig. 12.1.5 In an insulator, the Fermi level lies in the middle of a band gap. When you put charges near the insulator, electrons in the filled band can't shift to produce a net flow of charge through the insulator. The insulator can't conduct electricity.

can't reach the balcony to make use of its empty seats. This "insulator" theater would be unable to conduct people.

In a metal, the band of levels containing the Fermi level is only partially filled, and electrons can easily shift from filled to unfilled levels. In an insulator, the band below the Fermi level—the **valence band**—is full and the band above the Fermi level—the **conduction band**—is empty, making such shifts extremely difficult.

Even in an insulator, however, an electron can shift from a **valence level** (a level in the valence band) to a **conduction level** (a level in the conduction band) if something provides the necessary energy. One such energy source is light. When an insulator is exposed to the right type of light, that light can shift electrons from the material's valence band to its conduction band (Fig. 12.1.6).

Once electrons appear in the normally empty conduction band and empty levels appear in the normally full valence band, electrons can respond to electrostatic forces. They can shift from filled levels to nearby empty levels and thus travel through the material. Electrons can then enter the material from one side and leave from the other, so the material conducts electricity. Because light has made this insulator a conductor, we call the material a photoconductor.

Turning again to our analogy, light's role in the insulator theater is performed by a playful gorilla that walks about the ground floor, tossing patrons into the balcony. With some of the ground-floor seats suddenly empty and some of the balcony seats suddenly occupied by dazed theatergoers, the crowd can now respond to your request to move left. The gorilla has made the insulator theater a conductor of people—what you might call a "gorillaconductor."

Not all light causes photoconductivity in an insulator. That's because light is emitted and absorbed in energy packets or **quanta** called **photons**. As with an electron, a photon's energy is proportional to its frequency; the higher the frequency of light, the more energy each of its photons contains. To shift an electron across the large band gap in a typical insulator, high-energy, high-frequency light is needed; the insulator must be exposed to violet or even ultraviolet light.

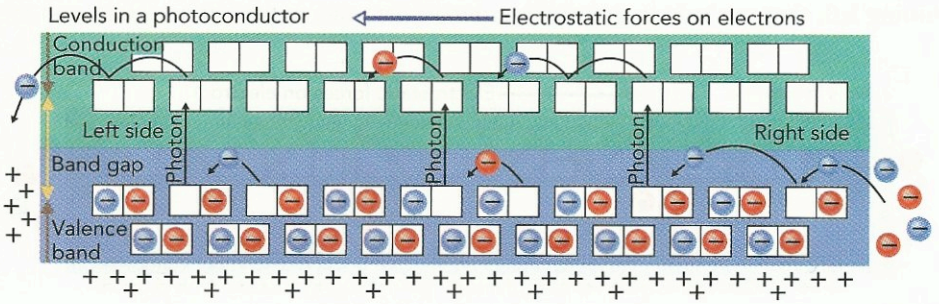


Fig. 12.1.6 When light strikes an insulator, the energy in its photons shifts some electrons from filled valence levels to empty conduction levels. Such shifts make it possible for electrons to move in response to electrostatic forces, so the insulator becomes an electrical conductor, a photoconductor.

Nature also provides materials with smaller band gaps that can be crossed with the help of low-energy, low-frequency red or even infrared light. These materials are called **semiconductors**, because their properties lie somewhere between those of conductors and insulators. Semiconductors have small band gaps, making it relatively easy for light, heat, or other types of energy to shift electrons between valence and conduction levels. In our analogy, a semiconductor theater is an insulator theater with a low balcony, so that even a baby gorilla can toss people into it.

For half a century, scientists and engineers have worked with semiconductors to produce an astonishing array of electronic devices. By carefully tailoring the shapes and chemical compositions of semiconducting materials such as silicon, germanium, and gallium-arsenide, they have created virtuoso instruments for electron waves in solids that are every bit as remarkable as the instruments for musical waves found in great orchestras. Of all these electronic instruments, the simplest is the semiconductor diode.

Check Your Understanding #4: Stop and Go Shopping

In many grocery checkout counters, a conveyor belt carries food to the register but stops when the food reaches the end and blocks a beam of light. How might a photoconductor be used to sense this blockage?

Answer: The beam of light shines on the photoconductor, allowing it to carry current and turn on the conveyer belt's motor. When food blocks the light beam, the photoconductor becomes an electrical insulator and the belt stops moving.

Why: Photoconductors are commonly used in light sensors. Light allows the photoconductor to carry current, and that current can be used to operate machinery, trigger a burglar alarm, or turn lights on or off. In the present case, it turns on the conveyor belt's motor.

Diodes

A **diode** is a one-way device for current; it allows current to flow through it in one direction but not in the other. Although diodes have taken many forms over the years, the diodes in power adapters and virtually all modern electronic devices are built from semiconductors.

A semiconductor diode is made by joining together two different semiconductors. These two semiconductors have been modified so that they don't have perfectly filled valence levels and perfectly empty conduction levels. Instead, they're **doped** with atomic impurities that either create a few empty valence levels (**p-type semiconductor**, Fig. 12.1.7*a*) or place a few electrons in the conduction levels (**n-type semiconductor**, Fig. 12.1.7*b*). These empty valence levels or conduction level electrons allow p-type and n-type semiconductors to conduct electricity. The doping atoms bring with them just the right amount of positive charge in their nuclei to keep both p-type and n-type semiconductors electrically neutral.

When a piece of p-type semiconductor touches a piece of n-type semiconductor, something remarkable happens: a **p-n junction** forms at the place where the two meet (Fig. 12.1.7*c*). To reduce their potential energies, higher energy conduction level electrons from the n-type semiconductor flow across the p-n junction and fill in empty lower energy valence levels in the p-type semiconductor. This electron flow creates separated charge. The n-type semiconductor acquires a positive net charge because it now has fewer electrons than positive charges. The p-type semiconductor acquires a negative net charge

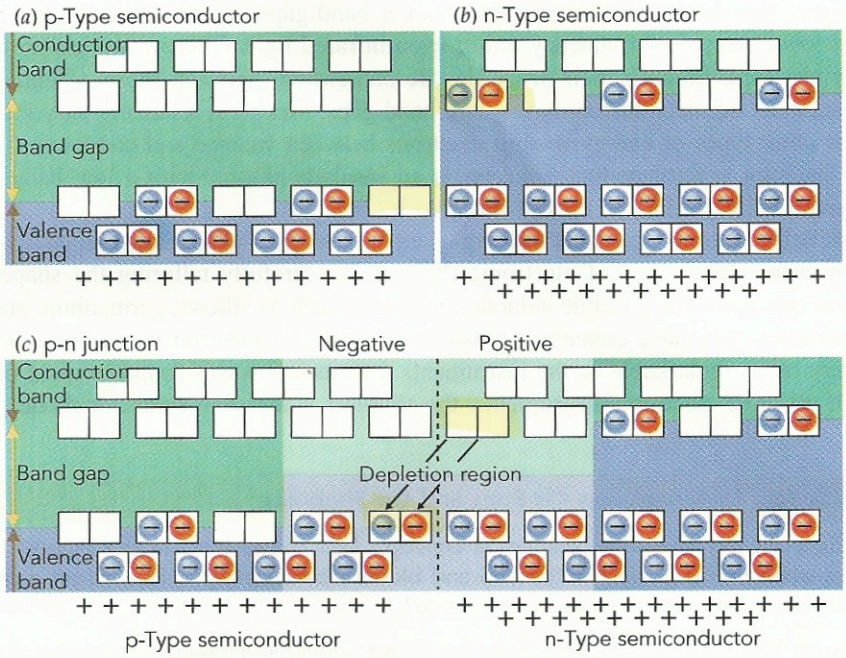


Fig. 12.1.7 (*a*) A p-type semiconductor has missing electrons (and missing positive atomic nuclei) and can conduct electricity through its partly filled valence band. (*b*) An n-type semiconductor has extra electrons (and extra positive atomic nuclei) and can conduct electricity through its partly filled conduction band. (*c*) When p- and n-type semiconductors touch, conduction level electrons shift from the n-type semiconductor to the p-type semiconductor, creating a thin, electrically polarized depletion region at the p-n junction.

because it now has more electrons than positive charges. Electrostatic forces from this separated charge oppose the further flow of electrons across the junction and gradually bring that flow to a halt. Everything is then in equilibrium.

Near the p-n junction, there is now a **depletion region**—an area in which electron flow has emptied all of the conduction levels and filled all the valence levels. With no conduction level electrons or empty valence levels left, the depletion region can't conduct electricity and charge can't move across the p-n junction. The depletion region is an insulator, and the two pieces of semiconductor have become a diode.

In our theater analogy, the p-n junction is analogous to a theater with two halves. In the left or "p-type" half, the balcony is empty, and even the ground floor has some empty seats. In the right or "n-type" half, the ground floor is filled and there are even a few people in the balcony. Since these two halves touch, people in the right balcony notice the empty seats in the left ground floor, and a few of them near the center of the theater clamber down from the right balcony to the left ground floor to take advantage of the better seats. Near the center of the theater, the ground floor is now filled and the balcony is empty, forming a depletion region in which no one can move left or right. The theater can't conduct people!

Let's now look at what happens when we attach wires to each semiconductor half and try using a battery to push electrons across the p-n junction. If we push electrons leftward, adding them to the n-type side and removing them from the p-type side, the depletion region becomes thinner and eventually vanishes (Fig. 12.1.8*a*). We're adding electrons to the n-type conduction levels and pushing them toward the p-n junction. We're also removing electrons from the p-type valence levels and pulling them away from the p-n junction.

The extra electrons on the n-type side and the missing electrons on the p-type side create a voltage difference between the diode's two halves. When the voltage of the p-type side reaches about 0.6 V above the voltage of the n-type side, the depletion region in a silicon diode disappears. Conduction level electrons in the n-type material then flow leftward across the junction and drop into empty valence levels in the p-type material. The p-n junction is conducting electric current.

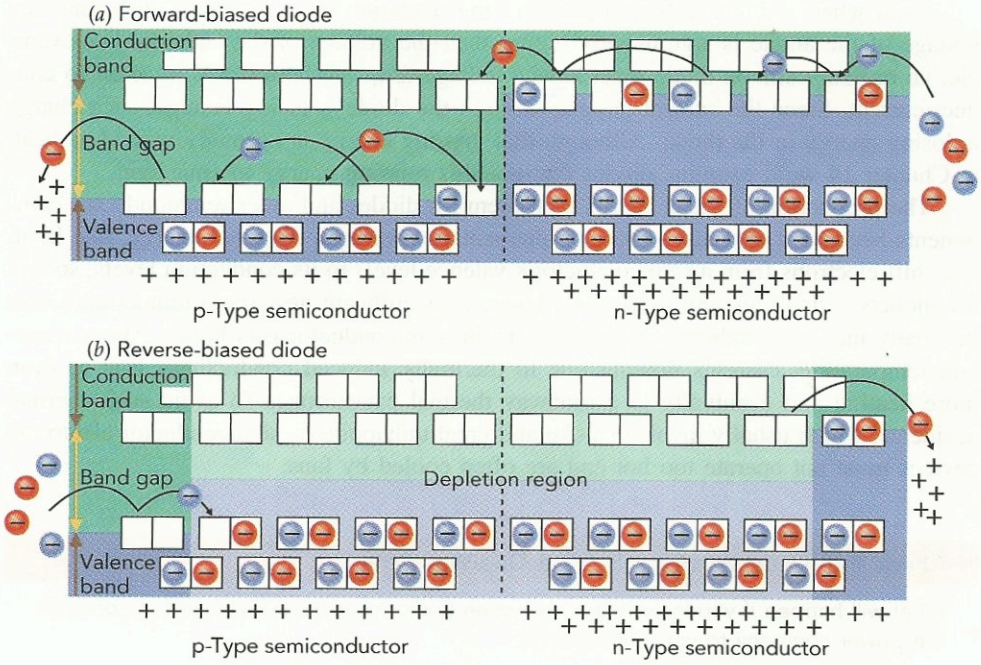


Fig. 12.1.8 (*a*) When you add electrons to the n-type side of a p-n junction and remove them from the p-type side, the depletion region vanishes, and current can flow across the junction. (*b*) When you add electrons to the p-type side and remove them from the n-type side, the depletion region thickens, and no current can flow across the junction.

In the theater analogy, we're adding people on the right to the n-type balcony and removing them on the left from the p-type ground floor. The new people in the n-type balcony can move about the empty seats and migrate toward the center of the theater. Similarly, the empty seats in the p-type ground floor allow people to shift about so that empty seats become available near the center of the theater. At that point, people in the n-type balcony can cross over to the p-type balcony and then climb down to the ground floor. There is a net leftward flow of people through the theater; the theater is conducting people from right to left.

What happens when we try to send electrons backward through the diode, pushing them into the p-type side and removing them from the n-type side (Fig. 12.1.8*b*)? In that case, the depletion region becomes thicker as we fill in empty valence levels in the p-type side and remove conduction level electrons from the n-type side. The widening depletion region prevents charge from moving, and no current flows across the p-n junction. It remains an insulator.

In the theater analogy, we're removing people on the right from the n-type balcony and adding them on the left to the p-type ground floor. Soon the n-type balcony is virtually empty and the p-type ground floor is essentially full. The entire theater is now a depletion region and behaves like the insulator theater. No one can move and the theater can't conduct people.

Since it allows current to flow in one direction but not the other, the p-n junction is a diode. For historical reasons, the diode's p-type side is called the *anode* and its n-type side is called the *cathode*. Current, which is the flow of positive charge, can only pass through a diode from its anode to its cathode. Since current naturally flows from higher voltage to lower voltage, a diode carries current only when it is **forward biased**—that is, when its anode has a higher voltage than its cathode. When it is **reverse biased**—when its anode has a lower voltage than its cathode—no current flows through the diode. This ability to control the direction of current flow is fundamental to converting alternating current into direct current.

Even when a diode is forward biased, the depletion region won't vanish until the voltage of the anode is significantly higher than the voltage of the cathode. For example, an ordinary silicon diode must have a voltage drop of about 0.6 V in order to conduct current. Since the current passing through the diode is losing voltage, each charge is losing energy in the diode. Although that missing energy is normally wasted as heat, in Chapter 14 we'll examine diodes that use this missing energy to emit light.

The production of waste heat is a problem for diodes and other semiconductor components because it can cause those components to overheat. Thermal energy, like light, can shift electrons from a semiconductor's valence levels to its conduction levels, so that it conducts a small amount of current. Though insignificant near room temperature, this thermally induced conductivity increases as the semiconductor gets hotter. Above a certain temperature, currents flowing due to thermally induced conductivity lead to even more heating and eventually to a runaway thermal catastrophe. To avoid such thermal accidents, which usually involve smoke and great unhappiness, semiconductor electronic devices must not operate too hot and are often cooled by fans.

Check Your Understanding #5: It's a One-Way Street

What will happen if you include a p-n junction (a diode) in the AC circuit that connects the power company to your table lamp?

Answer: Current will flow through the circuit only half the time, and your lamp will be dim.

Why: If you include a diode in an AC circuit, it will prevent current from flowing in one direction. Current will flow through the circuit only during the half of each power-line cycle when the diode's cathode is negatively charged and its anode positively charged. Since the lamp will receive only about half of its normal power, its filament won't reach normal operating temperature. The lamp will glow dimly, but the bulb will last an extraordinarily long time. Diodes are often used in this manner to create dim light levels in lamps or appliances.

Capacitors

The other new electronic component in the power adapter is its **capacitor**, a device that stores separated electric charge (Fig. 12.1.9). A capacitor consists of two conducting plates separated by a thin insulating layer (Fig. 12.1.10). When one plate is positively charged and the other is negatively charged, the opposite charges attract one another. This attraction allows the plates to store large quantities of separated charge, while leaving the capacitor as a whole electrically neutral.

Courtesy Lou Bloomfield

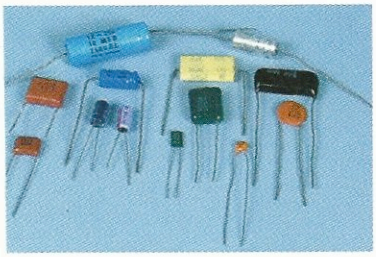


Fig. 12.1.9 Capacitors store separated electric charge. Each of these capacitors contains two conducting surfaces separated by a thin insulating layer.

You can charge a capacitor's plates by transferring charge from its negative plate to its positive one. The work you do during this transfer is stored in the capacitor as electrostatic potential energy and is released when you let the separated charge get back together. A charged capacitor acts like a battery when connected to a circuit because it pushes charge through the circuit from its positive plate and collects that charge from the circuit with its negative plate.

Since (positive) charge has more electrostatic energy on the positive plate than on the negative plate, the voltage of the positive plate is higher than the voltage of the negative plate. The voltage difference between the plates is proportional to the separated charge on them; the more separated charge the capacitor is holding, the larger the voltage difference between its plates.

This voltage difference also depends on the structure of the capacitor. Enlarging the plates allows the like charges on each plate to spread out, so that they repel one another less strongly. Thinning the insulating layer between the plates allows the opposite charges on the two plates to move closer together, so that they attract one another more strongly. Both of these changes lower the separated charge's electrostatic potential energy and, consequently, the voltage difference between the plates.

Because these changes allow the capacitor to store separated charge more easily, they increase its **capacitance**—that is, the separated charge it holds divided by the voltage difference between its plates. The SI unit of capacitance is the coulomb-per-volt, also called the **farad** (abbreviated F). A capacitor with a farad of capacitance stores an incredible amount of separated charge, even at a low voltage difference, while a capacitor with a billionth of a farad of capacitance is much more typical. The Greek letter μ in front of the F means millionths (μF or microfarads), the letter n in front of the F means billionths (nF or nanofarads), and the letter p in front of the F means trillionths (pF or picofarads). A capacitor's capacitance is marked on its wrapper, often in an abbreviated form.

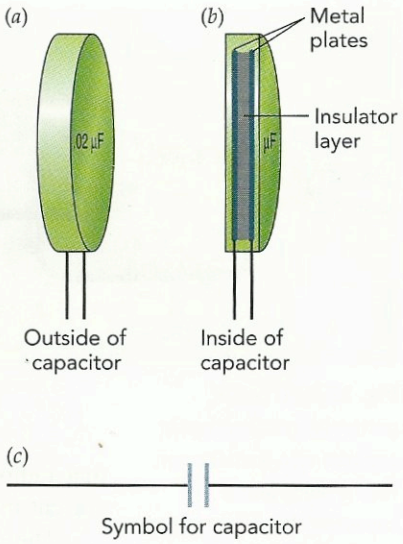


Fig. 12.1.10 (*a*) A capacitor is usually a disk or cylinder with two protruding wires. Its capacitance is printed on its surface. Inside (*b*), the wires are connected to two conducting plates that are separated by a thin insulating layer. (*c*) In a schematic diagram of an electronic device, the capacitor is represented by two parallel lines.

Check Your Understanding #6: Charging Up

Your stereo's amplifier obtains power from the power line. Since the power line delivers no power during the moments when its alternating current reverses direction, the stereo's power supply must store energy. How can it do this?

Answer: It can store the energy as separated charge on a large capacitor.

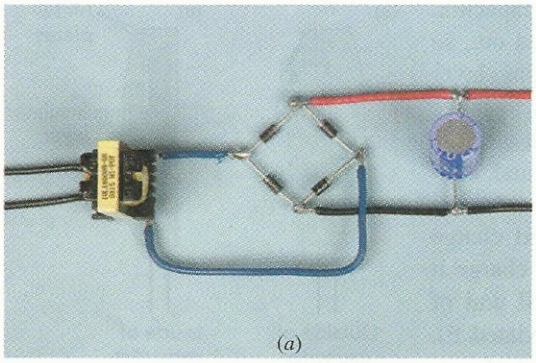
Why: The stereo's power supply saves energy in large electrolytic capacitors. During the times when the power line is providing plenty of electric power, the power supply uses that power to increase the separated charge in its capacitors. When the power line isn't providing power, the power supply draws energy out of the capacitors. Unfortunately, electrolytic capacitors age quickly and often leak their liquid electrolytes. Once one leaks, it can't store energy properly and your stereo will hum.

The Complete Power Adapter

Our power adapter uses a transformer, four diodes, and a capacitor to provide low-voltage direct current to the radio. The connections between these components are shown photographically in Fig. 12.1.11*a* and schematically in Fig. 12.1.11*b*. Engineers and scientists often use such **schematic diagrams** to represent complicated electronic devices, assigning a specific symbol to each electronic component and denoting the electrical connections between those components with lines.

Let's examine Fig. 12.1.11*a* from left to right. The leftmost component is the transformer. With its primary coil carrying alternating current from a 120-V AC outlet, its secondary coil develops an induced emf of 9-V AC. The secondary coil acts as a source of 9-V AC power.

If you were to connect a 9-V lightbulb to the two ends of this secondary coil, the coil's alternating induced emf would push an alternating current through the bulb's filament and the bulb would light up. However, if you were to connect the 9-V radio to this secondary coil, the coil's alternating emf would try to push an alternating current through



Courtesy Lou Bloomfield

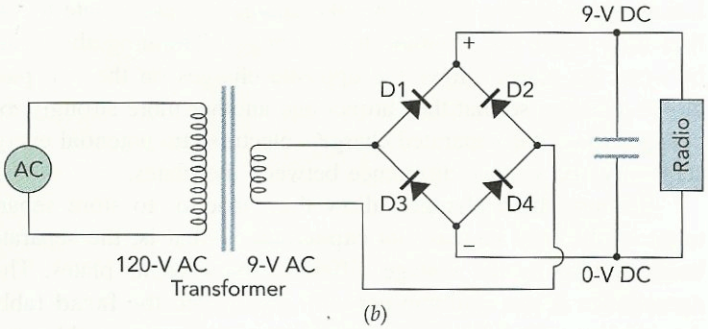


Fig. 12.1.11 (*a*) A particular power adapter consists of a transformer, four diodes, and a capacitor. (*b*) The same components shown schematically.

that radio and it wouldn't work. The transformer alone can't supply the steady direct current the radio requires.

The diodes in the middle of Fig. 12.1.11 solve the alternation problem by steering current so that it always flows through the positive power wire to the radio and returns from the radio through the negative power wire. Although the transformer's secondary coil continues to experience an alternating induced emf and carries an alternating current, diodes D1 and D2 guide current from the secondary coil to the radio and diodes D3 and D4 guide the returning current back to the secondary coil. Although the transformer itself is supplying AC power, the diodes allow the power adapter to supply DC power.

However, the diodes alone can't supply *steady* DC power. As the secondary coil's induced emf alternates, the voltage rise from the power adapter's negative power wire to its positive wire fluctuates up and down. That voltage rise peaks at about 12 V when the induced emf reaches its most positive or most negative value, but drops to zero while the induced emf changes sign. The transformer and diodes alone supply *pulsed* 9-V DC power—a form of direct current that offers the same average power as 9-V DC, but with severe voltage fluctuations. Since the radio will turn off between pulses, pulsed DC power won't do.

The capacitor solves the pulsing problem by storing charge and energy whenever the pulsed DC power is near its peak and releasing that charge and energy when the pulsed DC power is near its minimum. The capacitor acts like a rechargeable battery, charging whenever power is plentiful and discharging whenever it's not.

When the secondary coil's induced emf is strong, one of the diodes D1 or D2 is forward biased and guides current from the secondary coil to both the radio and the capacitor's positive terminal. At the same time, one of the diodes D3 or D4 is forward biased and guides current from both the radio and the capacitor's negative terminal back to the secondary coil. The radio receives the DC power it needs, and the capacitor gradually accumulates more separated charge. The voltage difference between the capacitor's terminals increases and it "charges."

When the secondary coil's induced emf is weak, all four diodes are reverse biased and current stops flowing through the coil. The capacitor takes over the job of supplying power to the radio. Current flows from the capacitor's positive terminal through the positive power wire to the radio, and it returns from the radio through the negative power wire to the capacitor's negative terminal. The radio still receives the DC power it needs, but now the capacitor gradually loses its separated charge. The voltage difference between its terminals decreases and it "discharges."

By charging and discharging in this manner, the capacitor "filters" the pulsed DC provided by the transformer and diodes. The capacitor smooths away both the voltage

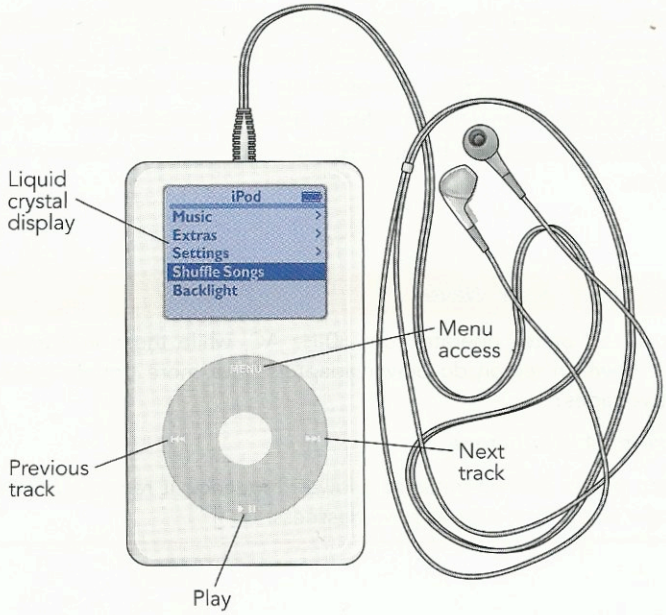
peaks and the voltage zeros. Although the voltage of this filtered DC power fluctuates slightly as the capacitor charges and discharges, the radio can operate from it. Like many electronic devices that accept power adapters, the radio has its own system for accommodating minor voltage fluctuations so that they don't affect its performance. As long as the radio receives a continuous current with approximately the correct voltage, it will work as though on batteries.

Check Your Understanding #7: Slow Waves

Power adapters in the United States operate from 60-Hz AC, while those in Europe operate from 50-Hz AC. In which region do power adapters have more trouble maintaining constant output voltages?

Answer: They have more trouble in Europe.

Why: Since the European power grid operates at a lower frequency, it requires power adapters to endure longer periods of relative powerlessness.



SECTION 12.2 Audio Players

Audio players have revolutionized portable music systems. Everywhere you look, people are sporting earpieces and listening to their favorite tunes with these little electronic marvels. Part computer and part stereo system, an audio player is a spectacular synthesis of some of the highest forms of modern electronic technology. Because they contain such a broad range of electronic components, audio players offer an excellent introduction to much of modern electronics.

To understand how audio players work, we'll need to look at how sound can be represented electronically and at how those electronic representations can be stored, retrieved, and ultimately used to recreate the sound itself. That exploration will take us all the way from the digital world of computers to the analog world of stereo amplifiers and headphones.

It will also expose us to that workhorse of modern electronics: the transistor. Early audio electronic devices were built with vacuum tubes, which were relatively bulky components that wasted power and aged quickly. Transistors have made audio electronics much more practical. They have also made computers so small and inexpensive that every audio player can have its own computer.

Questions to Think About: *What does it mean to store songs? How can a computer use numbers to represent music? Why does an audio player need electric power to operate? Why does an audio player become warm as it operates? Does the volume of the sound affect the battery life? What does an audio amplifier's power rating mean? How are electric power and sound volume related? How do the treble and bass controls of an audio player affect the sound?*

Experiments to Do: *Find an audio player or a related digital audio device such as CD or DVD player. Turn it on, and notice that it takes a short time to "wake up." You're*

observing the boot process of a computer. But if all of the computer's information is already inside it, why does it need to do so much work as its starts? As we'll soon see, the device's computer uses different types of memory, some of which is wiped clean when the audio player is turned off. With that tidbit in mind, try to imagine what is happening during the boot process.

Play some music and experiment with the sound controls. The volume control determines how much power reaches the headphones. Recall that a flashlight with a poor connection produces dim light. If you create a poor connection between the player and the earpiece, what happens to the volume? Where did the lost power go?

Now experiment with the bass and treble controls. If the player has any other audio effects, try them. Are you still hearing sound as it was originally performed? How do the player's tone settings influence the sound reproduction? Is the most perfect imitation of the original sound always what you want to hear?

Representing Sound: Analog and Digital

An audio player doesn't store sound any more than a DVD stores flickering light. Instead, the audio player stores a *representation* of sound that it can use to recreate that sound on demand. Tucked into the player's memory is enough information to reproduce some number of songs almost perfectly. Between the microphones that originally collected that information and the headphones that finally reconstruct the sound itself are a number of fascinating electronic processes. In this section, we'll explore the journey that this sound information takes between recording and playback. In doing so, we'll encounter much of the electronic basis not only for audio electronics, but for digital computers as well.

Our first task in trying to follow sound information as it moves through an audio player is to understand the two different techniques the player uses to represent sound: analog and digital. Let's begin that task by thinking about the recording process and about what information that process gathers from the original sound. In Chapter 9, we learned that sound in air is a density wave and that you hear a sound wave through its associated air pressure fluctuations. Audio recording mimics your hearing by measuring the air pressure fluctuations over time and saving those measurements in some useful format. Audio reproduction uses those measurements to reproduce a precise facsimile of the original air pressure fluctuations and thereby recreates the sound of the artists themselves.

Recording starts with microphones, which are basically sensitive electromechanical air pressure sensors. Playback ends with headphones or earpieces, which are electromechanical devices for influencing air density and pressure. Between the microphones and the headphones are some serious electronics.

The microphones and headphones connect the world of true sound with the world of electronic audio representations. What leaves the microphone is an electronic representation of the sound, not the sound itself. As the air pressure at the microphone fluctuates up and down about atmospheric pressure, the microphone produces a current that fluctuates back and forth about zero. This fluctuating current is an **analog representation** of the sound, meaning that it is a continuously variable physical quantity (current) that represents another continuously variable physical quantity (air pressure). Like any analog representation, the microphone is drawing an *analogy* between two continuously variable physical quantities: current is serving as an *analog* for air pressure. The headphones draw the reverse analogy.

Although parts of the audio player continue to use analog representations for the sound, other parts use a different representation: digital. In **digital representation**, a continuously variable physical quantity is represented by a set of physical quantities—a set of digits—each of which can have only a limited number of discrete values. In a digital

representation of sound, air pressure changes are measured numerically in some units, and those numerical values are then represented by sets of digits. Digital representations are widely used in computers, which represent everything imaginable as numbers and then represent those numbers as sets of digits.

For example, suppose the present air pressure at a microphone is 124 units above atmospheric pressure. We first represent the air pressure increase by the number *124* and then represent the number *124* by a set of digits. For example, *124* could be decomposed into the decimal digits 1, 2, 4 and then these decimal digits could be represented as three separate physical quantities, such as charges, currents, or voltages. Because each charge, current, or voltage only has to represent the integers from 0 to 9, its value doesn't have to be very accurate. If a voltage of 4 V is supposed to represent the digit 4, then 3.9 V or 4.1 V will still be understood to mean 4.

In everyday life, we usually break numbers into ones, tens, hundreds, thousands, and so on—the powers of 10—because we think and work in **decimal**. We could also break numbers into ones, twos, fours, eights, sixteens, and so on. Instead of using the powers of 10, as in decimal, we would be using the powers of 2. This system for representing numbers with the powers of 2 is called **binary**.

In decimal, *124* is written as 124, meaning that *124* contains 1 hundred (10^2), 2 tens (10^1), and 4 ones (10^0). When these pieces are added together, 100 + 20 + 4, you obtain *124*. In binary, *124* is written as 1111100, meaning that *124* contains 1 sixty-four (2^6), 1 thirty-two (2^5), 1 sixteen (2^4), 1 eight (2^3), 1 four (2^2), 0 twos (2^1), and 0 ones (2^0). When these pieces are added together, 64 + 32 + 16 + 8 + 4, they again total *124*. This apparently complicated way to represent even a fairly small number is actually quite useful. The number has been broken into pieces that have only two possible values. There is either a thirty-two in the number being represented or there isn't. The only two symbols you need when representing a number in binary are 0 and 1.

Because *124* is 1111100 in binary, you could represent 124 by the charge, current, or voltage of seven separate objects. The first five objects would contain 1's while the last two would contain 0's. For example, if the seven objects were capacitors, the first five might hold separated charge and the last two might hold no charge. A device that needed to know what number the capacitors represented would measure their charges. Finding separated charge in the first five capacitors (11111) and no separated charge in the last two (00), it would determine that the capacitors represent 1111100 binary or *124*.

Binary is useful because fast electronic devices that operate only between two extreme values are relatively easy to build: the current is on or off, the voltage is positive or negative, the charge is present or absent. It's much harder to build fast devices that deliver the specific currents, charges, or voltages needed for decimal or even analog representation. Analog representation is also susceptible to electronic imperfections and noise because an analog device that tries to represent *124* with a voltage of 124 V might accidentally produce 123 V or 125 V. Imagine a bank computer that couldn't tell $124 from $123 or $125! Although representing *124* in binary takes at least seven separate quantities, there is no confusion about which number is being represented.

Check Your Understanding #1: New Math

What number does binary 10000001 represent?

Answer: *129*

Why: Binary 10000001 contains only 1 hundred-twenty-eight (2^7) and 1 one (2^0). All the other powers of 2 are not present. Since 128 + 1 is *129*, that is the number represented by this binary value.

Resistors

Courtesy Lou Bloomfield

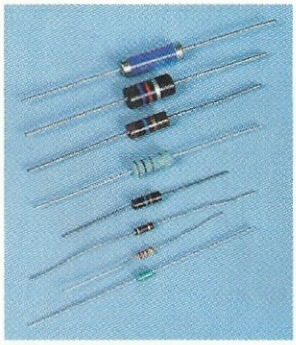


Fig. 12.2.1 Resistors are ohmic devices that impede current flow and produce a drop in voltage. They convert some of that current's electric power into thermal power. The larger resistors can handle more thermal power without overheating.

After that introduction to information representations, we're ready to look at how an audio player actually works with its information. We've already hinted at the fact that this information travels about the player as currents, voltages, and a few other physical quantities. But what tools does the player use to work with those physical quantities?

The player's tools are principally electronic ones and, happily, many are familiar to us. We have already encountered capacitors, inductors, transformers, and diodes, all of which are common in audio players and most other electronic devices. However, there are at least two other electronic components that no audio player or high-tech electronic device can be without: resistors and transistors.

Resistors complete a trio of electronic components that began with inductors and capacitors. As we saw in Chapter 11, an inductor uses its induced emf to produce a voltage rise that's proportional to how quickly current is changing with time. In the previous section, we learned that a capacitor uses its ability to store charge to produce a voltage rise that's proportional to the sum of current over time. What we're missing is a device that uses its electrical resistance to produce a voltage rise that's simply proportional to current. That missing device is called a **resistor**.

A resistor is just two wires connected by an ohmic device, an imperfect conductor of electricity (Figs. 12.2.1 and 12.2.2). Since current flows through an ohmic device only if there's an electric field pushing it forward, a current-carrying resistor must have a voltage drop across it. In accordance with Ohm's law (see Section 10.3), that voltage drop is proportional to the current in the resistor.

However, the voltage drop through a resistor is also proportional to the resistor's electrical resistance—to how imperfect a conductor it is. The larger its resistance, the less current flows through the resistor at a particular voltage drop. Some are relatively good conductors ("low" resistance), while others are relatively poor conductors ("high" resistance).

As we saw in Section 10.3, a resistor's electrical resistance is defined as the voltage drop through it divided by the current flowing through it and is measured in ohms (abbreviated Ω). A resistor with a few ohms of resistance is nearly a good conductor, while a resistor with a few million ohms of resistance is nearly an insulator. A k in front of the Ω means thousands (kΩ or kilohms), and an M in front of the Ω means millions (MΩ or megohms). Thus a 100-kΩ resistor has a resistance of 100,000 Ω and a 10-MΩ resistor has a resistance of 10,000,000 Ω. A resistor's resistance is marked on its cylindrical body, often in the form of brightly colored stripes. Ten different colors represent the digits 0 through 9, as well as various powers of ten, so that a resistor with stripes brown (1), black (0), and red (×100) is a 1000-Ω resistor.

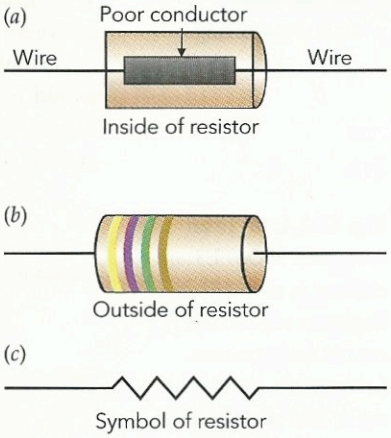


Fig. 12.2.2 (*a*) A resistor is two wires with an imperfect conductor of electricity between them. (*b*) It's usually encased in a cylindrical shell, with colored stripes to indicate its resistance. (*c*) In a schematic diagram of an electronic device, the resistor is represented by a zigzag line.

Check Your Understanding #2: A Waste of Energy

Your radio produces sound when its amplifier allows current from its power supply to flow through its speaker. During a quiet moment, the amplifier sends only a small current through the speaker and that current experiences only a small voltage drop. The current thus retains most of its electric power. How can the radio use up the current's remaining power before returning it to the power supply for reuse?

Answer: The amplifier can send the current through a resistor.

Why: By passing the current through a resistor, the amplifier converts most of the current's remaining electric power into thermal power. The current leaves the resistor with only enough electric power to carry it back to the power supply for reuse.

Transistors

Courtesy Lou Bloomfield

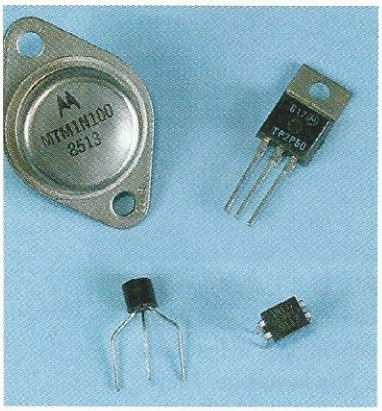


Fig. 12.2.3 These MOSFETs make it possible for small electric charges to control large electric currents. The larger transistors can handle more electric power and thermal power without overheating.

Invented in 1948 by three American physicists, William Shockley (1910–1989), John Bardeen (1908–1991), and Walter Brattain (1902–1987), **transistors** (Fig. 12.2.3) are key elements in nearly all modern electronic equipment. Like diodes, transistors are built from doped semiconductors—semiconductors such as silicon to which chemical impurities have been added. However, unlike diodes, which simply prevent current from flowing backward through a single circuit, transistors allow the current in one circuit to control the current in another circuit.

There are many types of transistors, but the simplest and most important type is the *field-effect transistor*. Actually, even here there are several varieties, so we'll focus on the one that's most widely used in audio players, video equipment, and computers: the *n-channel metal-oxide-semiconductor field-effect transistor* or *n-channel MOSFET*. Despite its complicated name, the n-channel MOSFET is a relatively simple device, consisting principally of three semiconductor layers and a nearby metal surface (Fig. 12.2.4). The three layers are called the *drain*, the *channel*, and the *source*, and the metal surface is called the *gate*.

The drain and the source consist of a strongly doped n-type semiconductor (many conduction level electrons), and the channel between them consists of a lightly doped p-type semiconductor (a few empty valence levels). When those three layers touch, they form two back-to-back p-n junctions, and conduction level electrons from the drain and source flow into the channel to fill its few empty valence levels (Fig. 12.2.5*a*). The completed transistor is thus left with a vast depletion region—a region devoid of empty valence levels or occupied conduction levels—extending all the way from its drain to its source. With nothing to convey charge through its channel, the transistor can't conduct current between its drain and source.

However, if more electrons could be coaxed into the channel somehow, those electrons would have to go into the channel's conduction levels and the channel would then behave like an n-type semiconductor. With an n-type channel sandwiched between an n-type drain and an n-type source, the p-n junctions would vanish and so would the depletion region. The three layers would become, in effect, a single piece of n-type semiconductor, and the transistor would then be able to conduct current between its drain and source.

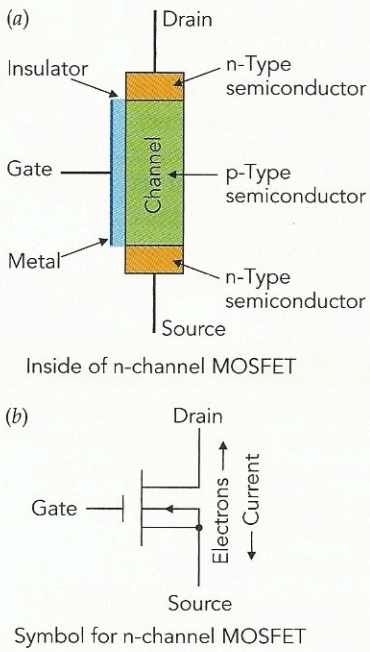


Fig. 12.2.4 (*a*) In an n-channel MOSFET, the channel is normally a depletion region that cannot carry current between the source and drain. But when positive charge on the gate attracts electrons into the channel, the channel becomes an n-type semiconductor and allows current to flow. (*b*) The symbol representing an n-channel MOSFET in a schematic diagram.

Drawing extra electrons into the channel from outside the transistor is the task of the metal-like gate. Separated from the channel by an incredibly thin insulating layer, the gate controls the channel's ability to carry current. When a tiny positive charge is placed on the gate through a wire, it attracts electrons into the channel's conduction levels and the transistor begins to conduct current (Fig. 12.2.5*b*). The more positive charge there is on the gate, the more electrons enter the channel and the more current can flow through the transistor. In effect, the transistor behaves like an adjustable resistor with a resistance that decreases as the positive charge on its gate increases.

We can now understand the n-channel MOSFET's name. "n-Channel" refers to the channel's n-type behavior when its gate is positively charged and the transistor can carry current. Although the

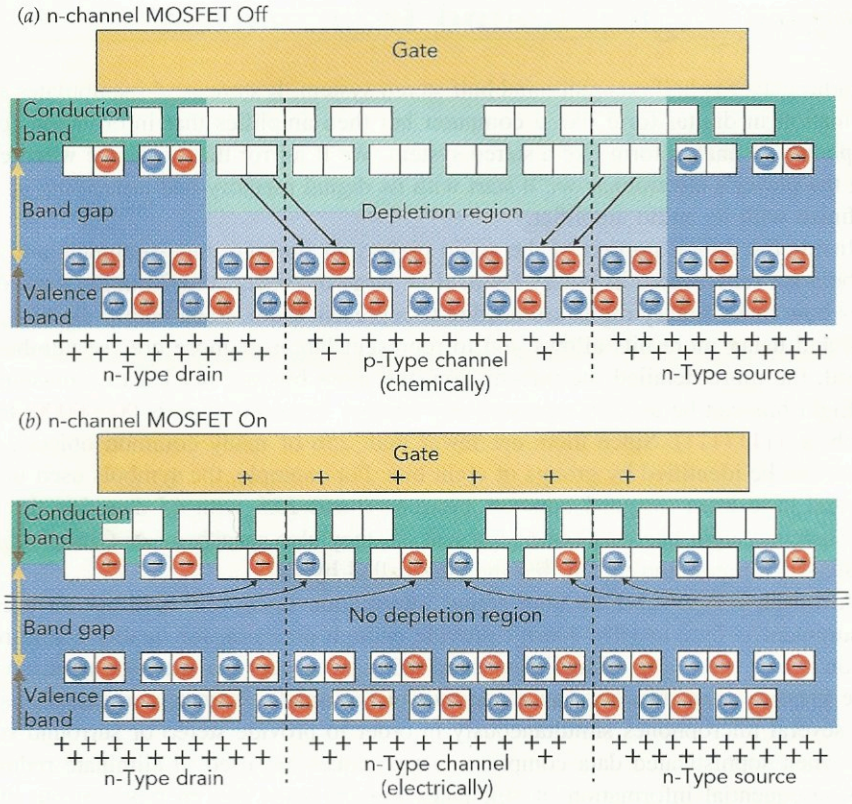


Fig. 12.2.5 (*a*) When an n-channel MOSFET is formed, conduction level electrons from the n-type source and drain fill the empty valence levels of the p-type channel and form a vast, insulating depletion region. (*b*) But when positive charge is placed on the nearby gate, it attracts electrons from outside the MOSFET into the channel's conduction levels and turns the entire structure into a conducting n-type semiconductor.

channel is chemically p-type, it becomes electrically n-type when extra electrons are drawn into it and it acquires a negative net charge. "Metal-oxide-semiconductor" indicates that the metal gate is separated from the semiconductor channel by a thin insulating layer of oxide. This insulator is agonizingly easy to puncture, which is why so many electronic devices can be damaged by static electricity. "Field-effect transistor" indicates that the electric field from charge on the gate is what draws electrons into the channel and controls the current flow through the transistor.

Check Your Understanding #3: Power and Control

Widening the channel of an n-channel MOSFET allows it to handle more current between its source and drain. However, the enlarged transistor needs more positive charge on its gate to control that current. Explain.

Answer: The larger transistor also has a larger gate. With more surface over which to spread its charge, the gate needs more positive charge in order to draw conduction level electrons into the channel.

Why: MOSFETs range in size from remarkably small (less than 0.1 μm^2) to relatively large (several square-millimeters). The smallest ones are used in computer chips, where millions of MOSFETs are created on a single wafer of silicon only a centimeter square. A tiny charge on the gate of one of these MOSFETs will allow it to conduct current. The largest MOSFETs are used in power control devices such as amplifiers and power supplies. These transistors have large gates, and much more charge is needed to allow one of them to conduct current.

Storing Digital Sound Information

An audio player is half computer and half stereo system. It stores and manipulates sound information in digital form like a computer but then amplifies that information for the headphones in analog form like a stereo system. We'll mirror that sequence when examining the player's electronics: we'll start with its digital memory and processing systems and finish with its audio amplifier.

Inside the digital portion of the audio player, air pressure measurements and other numbers are represented in binary form. How large or precise those numbers are determines how many binary digits are needed to represent them. Each binary digit is called a **bit**, and using more bits allows you to represent larger or more precise numbers. In general, the more detailed the information, the more bits are needed to represent it.

Eight bits can be used to represent any number from *0* (which is 00000000) to *255* (which is 11111111). Since there are fewer than 256 of many common objects, these objects can be identified by groups of eight bits. For example, the symbols used in ordinary text have been assigned numbers between *0* and *255*, with *65* denoting the letter "A." Since the eight bits 01000001 represent *65*, they also specify an A. Groups of eight bits are so common and useful that they are called **bytes**.

Although it's possible to store sound information using one byte per air pressure measurement, a byte usually doesn't provide enough precision for quality sound reproduction. More often, digital audio is saved using two bytes per pressure measurement. These pressure measurements are made tens of thousands of times per second, usually from several microphones simultaneously in order to provide stereo or surround sound. Even when sophisticated data compression techniques are used to eliminate redundant or inconsequential information, it still takes a great many bits to represent an album. Thus an audio player needs a lot of memory.

There are several ways in which the audio player, like any computer, stores a bit. In its main working memory (often called random access memory or RAM), each bit is a tiny capacitor that uses the presence or absence of separated electric charge to denote a 1 or a 0. The player stores a bit by producing or removing separated charge and recalls the bit by checking for that charge.

Each capacitor is built right at the end of its own n-channel MOSFET. That MOSFET controls the flow of charge to or from the capacitor. To store or recall a bit, the audio player places positive charge on the gate of the MOSFET so that the MOSFET becomes electrically conducting. The memory system can then transfer charge to or from the bit's capacitor.

Storing the bit is relatively easy; the player simply sends the appropriate charge through the MOSFET to the capacitor. Recalling the bit is harder, because the charge on the capacitor is extremely small. Sensitive amplifiers in the memory system detect any charge flowing through the MOSFET from the capacitor and report what they find to the audio player. Since this reading process removes charge from the capacitor, the memory system must immediately store the bit again.

Unfortunately, these tiny capacitors can't hold separated charge forever because it leaks out to their surroundings. Memory that uses charged capacitors to store bits is called dynamic memory and must be refreshed (read and restored) hundreds of times each second to ensure that a 1 doesn't accidentally switch to a 0 or vice versa.

Dynamic memory is also volatile—its contents are lost when the audio player turns off. To conserve its batteries, the player keeps its music information in nonvolatile memory—memory that doesn't need power to retain its information. New possibilities for nonvolatile memory appear almost every year, but at present the three leading forms are

flash, magnetic disk, and optical disk memories. We'll concentrate on flash and magnetic disk memory here and save optical memory for Section 15.2.

Flash memory resembles dynamic memory in that each bit is stored as the presence or absence of charge associated with a MOSFET. In flash memory, though, that charge resides on the MOSFET's floating gate—a second, unattached gate located in the insulating layer between the channel and the normal gate. Since this floating gate is surrounded by insulator, it can keep its charge for decades. As long as that charge is present, it will determine the MOSFET's conductivity and whether the bit is a 0 or a 1.

Reading bits from flash memory is easy, but storing them is a challenge. The same isolation that traps charge on the floating gate for years makes that charge difficult to change. To add or remove electrons from the floating gate, the memory system applies relatively large voltages to the MOSFET's source, drain, and normal gate, and the resulting strong electric fields permit electrons to cross through the insulation separating the channel from the floating gate.

To add electrons to the floating gate, the electric fields are arranged so they accelerate channel electrons to such high speeds that those electrons simply burrow right through the insulating layer to the floating gate. To remove electrons from the floating gate, the electric fields are arranged so that the floating gate's electron standing waves are distorted into the insulator. When these distorted waves reach far enough into the insulator, electrons begin to leak through it into the channel via a process known as *quantum tunneling*. We'll return to explore quantum tunneling in Chapter 16.

Flash memory is fast to read but relatively slower to write. Moreover, the electron-burrowing process causes cumulative damage to the insulating layer and limits the number of times flash memory can be written. An audio player uses a mixture of dynamic memory and flash memory: it does its computational work in dynamic memory but retains its long-term information in flash memory.

However, there's another memory concept that remains more cost-effective than flash memory for storing vast amounts of information: magnetic disk memory. Audio players that store tens of thousands of songs usually contain magnetic disks. Also called hard disks, these devices use the magnetic effects that we discussed in Chapter 11 to store music or other information.

Just as the magnetic strip on a credit card (Fig. 11.1.6) can store information in the locations of its magnetic poles, the surface of a magnetic disk can store information in the orientations of its magnetic poles. Actual hard disks are smooth aluminum platters that have been coated with hi-tech hard magnetic materials. Using microscopic electromagnets to write magnetic poles and sophisticated semiconductor magnetic sensors to read them, modern hard disks can pack almost a quarter-billion bits into a square-millimeter of surface (about 16 gigabytes per square-inch). Simply locating those microscopic bits on platters that rotate over 100 times per second is an electromechanical tour de force, yet these disks do it routinely even while you are jogging with your audio player.

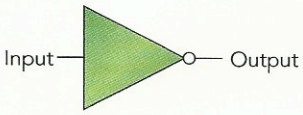
Check Your Understanding #4: **Like Sending a Letter to Yourself**

Every few thousandths of a second, a computer's memory system stops briefly to read and then rewrite every bit in its dynamic memory. What is going on?

Answer: The computer is making sure that the charge stored on each capacitor in the dynamic memory adequately represents that bit's contents.

Why: Since charge leaks quickly from the capacitors in dynamic memory, the contents of each bit must be refreshed many times a second. This refreshing process, reading each bit and storing it back into memory, slows the computer down slightly.

The Audio Player's Computer



Input	Output
1	0
0	1

Fig. 12.2.6 An inverter, shown here symbolically, produces one output bit that is the inverse of its one input bit.

We've seen how sound information can be represented and stored as bits, so now let's look at how an audio player's computer works with those bits. This digital processing is done by electronic devices that take groups of bits as their inputs and produce new groups of bits as their outputs. Since their output bits are related to their input bits by the rules of logic, these electronic devices are called logic elements.

The simplest logic element is the inverter, which has only one input bit and one output bit. Its output is the inverse of its input (Fig. 12.2.6). If an inverter's input bit is a 1, then its output bit is a 0 and vice versa. Inverters are used to reverse an action—turning a light on rather than off or starting a song rather than stopping it. Inverters are also used as parts of more complicated logic elements.

But inverters aren't just abstract logic elements; they're real electronic devices. They act on electrical inputs and create electrical outputs. In an audio player's computer, inverters and other logic elements represent input and output bits with electric charge. Positive charge represents a 1 and negative charge represents a 0. Thus when positive charge arrives at the input of an inverter, the inverter releases negative charge from its output.

Inverters and other logic elements are usually constructed from both n-channel and p-channel MOSFETs. We've already seen that n-channel MOSFETs conduct current only when their gates are positively charged. p-Channel MOSFETs are just the reverse, conducting current only when their gates are negatively charged. The drain and source of a p-channel MOSFET are made from p-type semiconductor, and the channel is made from n-type semiconductor. Since n-channel and p-channel MOSFETs are exact complements to one another, logic elements built from them are called complementary MOSFET or CMOS elements. An audio player's computer is built almost entirely from CMOS elements.

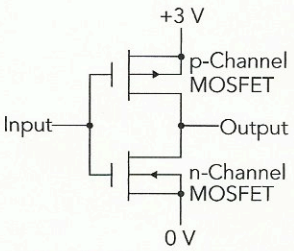


Fig. 12.2.7 When negative charge arrives at the input of a CMOS inverter, its p-channel MOSFET (*top*) permits positive charge to flow to the output. When positive charge arrives at the input, the n-channel MOSFET (*bottom*) sends negative charge to the output.

A CMOS inverter consists of one n-channel MOSFET and one p-channel MOSFET (Fig. 12.2.7). The n-channel MOSFET is connected to the negative terminal of the computer's power supply and controls the flow of negative charge to the inverter's output. The p-channel MOSFET is connected to the power supply's positive terminal and controls the flow of positive charge to the output. When negative charge arrives at the inverter's input and moves onto the gates of the MOSFETs, only the p-channel MOSFET conducts current and the output becomes positively charged. When positive charge arrives at the input, only the n-channel MOSFET conducts current and the output becomes negatively charged.

A computer, however, needs logic elements that are more complicated than inverters. One such element is the Not-AND or NAND gate. This logical element has two input bits and one output bit, and its output bit is 1 unless both input bits are 1's (Fig. 12.2.8). It's called a Not-AND gate because it's the inverse of an AND gate. An AND gate produces a 0 output unless both input bits are 1's. Simple memoryless logic elements are often called gates.

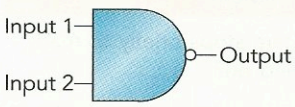


Fig. 12.2.8 The output bit of a Not-AND or NAND gate, shown here symbolically, is a 1 unless both input bits are 1's.

Input 1	Input 2	Output
1	1	0
1	0	1
0	1	1
0	0	1

A CMOS NAND gate uses two n-channel MOSFETs and two p-channel MOSFETs (Fig. 12.2.9). The two n-channel MOSFETs are arranged in **series**—one after the next—so that current passing through one must also pass through the other. If either transistor has negative charge on its gate, no current can flow through the series. Components arranged in series all carry the same current, but they may experience different voltage drops.

The two p-channel MOSFETs are arranged in **parallel**—one beside the other—so that current can flow through either one of them to the output. If either transistor has negative charge on its gate, current can flow from one side of the pair to the other. Components arranged in parallel share the current they receive through one wire and deliver it together to the second wire. Although parallel components may share the current unevenly among themselves, they all experience the same voltage drop.

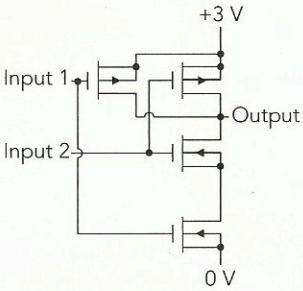


Fig. 12.2.9 A CMOS NAND gate has two input bits. When negative charge arrives through either input, the chain of n-channel MOSFETs (*bottom*) stops conducting current and one of the two p-channel MOSFETs (*top*) permits positive charge to reach the output. Only if both inputs are positively charged will negative charge reach the output.

Parallel and Series Wiring

Connection in Series: Components that are wired in series, one after the other so that they form a chain, all carry the same current but can have different voltage drops. The total voltage drop from the start of the chain to its end is the sum of the individual voltage drops through the components.

Connection in Parallel: Components that are wired in parallel, one beside the other so that they all connect the same pair of wires, have the same voltage drop but can carry different currents. The total current flowing between those wires is the sum of the individual currents through the components.

If negative charge arrives at either input of the CMOS NAND gate, the series of n-channel MOSFETs will be nonconducting and one of the p-channel MOSFETs will deliver positive charge to the output. However, if positive charge arrives at both inputs, both p-channel MOSFETs will be nonconducting and the series of n-channel MOSFETs will deliver negative charge to the output. Thus the CMOS NAND gate has the correct logic behavior.

These two logic elements, inverters and NAND gates, can be combined to produce any conceivable logic element. For example, they can be used to build an adder, a device that sums the numbers represented by two groups of input bits and produces a group of output bits representing that sum. These adders can themselves be used to build multipliers, and multipliers can be built into still more complicated devices. In this fashion, the simplest logic elements can be used to construct an entire computer.

Actually, a computer isn't built exclusively from NAND gates and inverters. To improve its speed and reduce its size, it uses a few other basic logic elements as well. Like the CMOS NAND gate and inverter, these elements are constructed directly from n-channel and p-channel MOSFETs.

All of these logic elements are wired together in an intricate pattern to create a complete computer (Fig. 12.2.10). In an audio player, this computer retrieves and organizes music information and prepares it for the playback electronics, which are not digital. The computer's last act is to deliver the digital music information, the air pressure measurements, to a digital-to-analog converter or *DAC*. This electronic device is the interface between the two representations of information, digital and analog. The music information leaves the DAC as a voltage that's proportional to air pressure. This voltage is the input for the audio player's main analog component: its audio amplifier. Actually, the player has two complete analog audio systems so that it can produce stereo sound. But since those systems are identical, we'll focus on only one of them.

Courtesy Intel Corporation

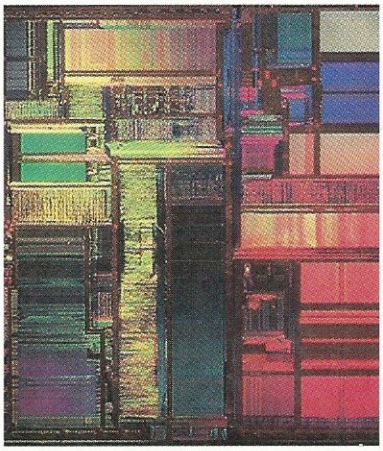


Fig. 12.2.10 This microscope photograph shows an integrated circuit microprocessor—approximately a computer on a chip. Aluminum strips connect millions of MOSFETs and other components that have been formed by photographic techniques on the surface of a thin wafer of silicon.

Check Your Understanding #5: Getting It Together

How could you use inverters and NAND gates to create an AND gate, a logic element that has two inputs and one output, with the output being 1 only if both of the inputs are also 1's?

Answer: You could connect an inverter to a NAND gate so that the output signal of the NAND gate is the input signal of the inverter. When both of the NAND gate's input signals are 1's, it will produce an output of 0. This 0 will arrive at the inverter, which will invert it and yield an output of 1.

Why: Connecting logic elements together one after the next is the standard method for producing more complicated logic elements. In this case, two elements produce a third.

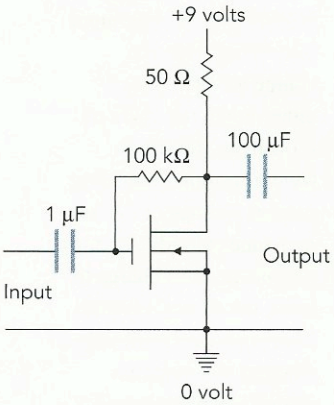


Fig. 12.2.11 A simple audio amplifier can be built with one n-channel MOSFET, two resistors, and two capacitors. A 9-V battery powers the device.

The Audio Player's Audio Amplifier

The fluctuating voltage provided by the audio player's DAC is often called an *audio signal* because it represents audio information. Many analog or digital representations of information are called **signals**, including video signals, data signals, and even turn signals. But although the player's audio signal contains all the information needed to reproduce the original sound, in convenient analog format, it doesn't have the power that the headphones need to produce that sound at a reasonable volume. Something must first enlarge the audio signal; it needs to be *amplified*.

Devices that enlarge various characteristics of signals are called **amplifiers**. An audio amplifier is an amplifier that's designed to boost signals in the frequency range that we hear or feel (20 Hz to 20,000 Hz). It has two separate circuits—an input circuit and an output circuit—and it uses the small current passing through its input circuit to control a much larger current passing through its output circuit. In this manner, the amplifier provides more power to its output circuit than it receives from its input circuit. Since energy is conserved, an amplifier needs a separate power source to provide its amplification—in this case, the 9-V battery.

Figure 12.2.11 shows the schematic diagram for a simple audio amplifier, built from the components we've just studied. This amplifier has only five components: an n-channel MOSFET, two resistors, and two capacitors. It draws power from a 9-V battery (or an equivalent power adapter) and amplifies a tiny alternating current in its input circuit into a large alternating current in its output circuit.

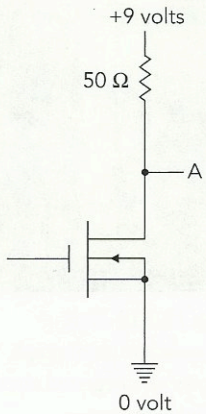


Fig. 12.2.12 The voltage at A depends on the resistance of the MOSFET. The lined triangle at the bottom signifies connection to ground (often the earth itself).

To understand how this amplifier works, let's first remove everything but the MOSFET and the 50-Ω resistor (Fig. 12.2.12). These two components are in series, so any current that passes through one must also pass through the other. When the MOSFET doesn't conduct current, no current flows through the 50-Ω resistor and it experiences no voltage drop. So the voltage at A is 9 V. However, if the transistor does conduct current, a voltage drop will appear through the 50-Ω resistor and the voltage at A will decrease.

The transistor will conduct current only if positive charge is put on its gate. That can be done by connecting the gate to A with a 100-kΩ resistor (Fig. 12.2.13). Since A is at 9 V, it is positively charged and pushes charge toward anything at lower voltage. Current flows slowly through the resistor from A to the gate. However, as positive charge accumulates on the gate, the transistor begins to conduct current and the voltage at A drops. When the voltage at A reaches the voltage on the gate, current stops flowing through the resistor.

The amplifier is then in a stable equilibrium; A has a voltage of approximately 5 V, and the transistor's gate has a modest amount of charge on it. The 100-kΩ resistor

provides the transistor with **feedback**—that is, it provides the transistor with information about the present situation at A that the transistor can use to correct or improve that situation. Although the feedback is slowed by the resistor's large electrical resistance, it perpetually acts to return the voltage at A to its equilibrium value. If the transistor conducts too little current, charge flows onto its gate and makes it conduct more. If the transistor conducts too much current, charge flows off its gate and makes it conduct less.

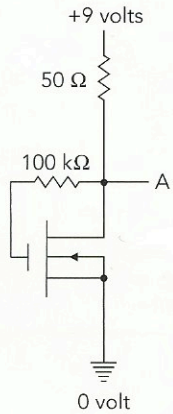


Fig. 12.2.13 The 100-k Ω resistor transfers positive charge to the gate until the voltage at A drops to about 5 V.

The amplifier is now exquisitely sensitive to small changes in the charge on the transistor's gate. If you add just a tiny bit more positive charge to the gate, down goes the voltage at A. If you remove just a tiny bit of positive charge from the gate, up goes the voltage at A. Although current in the feedback resistor tries to undo these changes, it acts too slowly to oppose short–time scale variations. The amplifier's input signal successfully adds or subtracts positive charge from the gate, and the amplifier's output signal emerges from A.

The amplifier has two input wires. An analog audio signal's current flows into the amplifier through one wire and returns through the other. However, the audio signal is not connected directly to the gate. Instead, it's connected to the gate through a capacitor (Fig. 12.2.14). In addition to storing charge and energy, a capacitor can transfer current between two wires that have different voltages. Such voltage flexibility is important in battery-powered audio amplifiers that must do their amplifying exclusively with positive voltages. Aided by input and output capacitors, our audio amplifier can have an average operating voltage of about +5 V while it also has average input and output voltages of 0 V.

To see how a capacitor passes along current, let's watch input current flow rightward into our amplifier's input capacitor. As that current's positive charge accumulates on the capacitor's left plate, it attracts negative charge onto the capacitor's right plate and away from the gate. The capacitor remains electrically neutral but the gate becomes more positively charged. Overall, the capacitor has conveyed input current to the gate, even though no charge has actually passed through its insulating layer and its two plates remain at different voltages.

With the help of the input capacitor, the amplifier's fluctuating input current produces a fluctuating charge on the transistor's gate, and the voltage at A fluctuates as a result. Even a tiny fluctuating current on the input wires creates a large fluctuating voltage at A.

This fluctuating voltage is responsible for sending a fluctuating current through the headphones. Although headphones are not truly ohmic devices, they respond to fluctuating voltages by carrying fluctuating currents. By applying a fluctuating voltage drop across the headphone's two wires, the amplifier can cause it to carry a fluctuating current and produce corresponding pressure fluctuations and sound.

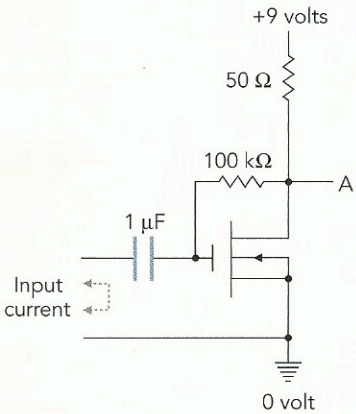


Fig. 12.2.14 Because current flowing back and forth through the two input wires affects the charge on the transistor's gate, it also affects the voltage at A.

However, the voltage at A averages about 5 V, while the headphones expect an average voltage drop of 0 V. To convey the fluctuating voltages and currents from A to the headphones while eliminating their large voltage difference, our amplifier connects them via an output capacitor (Fig. 12.2.15). As before, the fluctuations in current and voltage on the output capacitor's left plate are mirrored by current and voltage fluctuations on its right plate. Even though the amplifier operates at a high average voltage, the output signal for the headphones has an average voltage of 0 V.

Tiny fluctuating currents in our amplifier's input circuit produce large fluctuating currents in its output circuit. This amplifier works remarkably well, given its simplicity. If you connect a microphone to the input wires and headphones to the output wires, the headphones will do a surprisingly good job of reproducing the sound in the microphone.

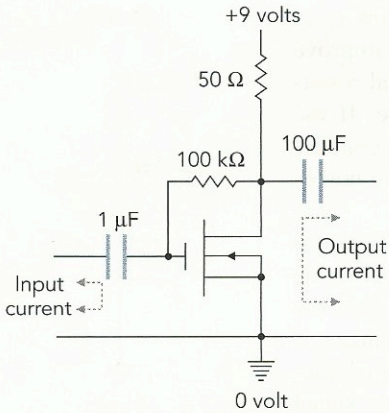


Fig. 12.2.15 The amplifier causes currents to flow back and forth through the two output wires. The alternating current in the output wires is a good replica of the alternating current in the input wires, only larger.

However, our simple amplifier isn't perfect. It distorts the sound somewhat, and it doesn't handle all frequencies or amplitudes of sound equally. It also wastes a large amount of electric power heating the 50-Ω resistor. The amplifiers in audio players carefully correct for these problems. Most use feedback to make sure that their output signals are essentially perfect replicas of their input signals, only larger. They sense their own shortcomings and correct for them.

Perfect replication of the input signal isn't always desirable however. Sometimes you want to boost the volume for part of the sound. The treble and bass controls on an audio player allow you to selectively change the volumes for the high- and low-frequency portions of the sound, respectively.

An amplifier is typically rated according to the peak power it can supply to the headphones (or speakers), and its average power should never reach that value. Yet the amplifier can reach its peak power during a passage that's not particularly loud. That's because sound waves often interfere with one another (see Section 9.3 to review wave interference) and when their crests and troughs coincide at the microphone, constructive interference can briefly produce enormous pressure fluctuations.

To reproduce those overlapping waves properly, the audio amplifier must be able to provide several times its average power, though only for a moment. If the amplifier can't deliver that much power, the audio signal it sends to the headphones or speakers will be distorted and the sound will be unpleasant. That's why audiophiles often use powerful amplifiers even when they're playing quiet music. Most modern amplifiers are designed cleverly so that they consume only a little more electric power than they actually need to produce their outputs. They consume little power during quiet passages, but can still provide great power during the loud moments.

As for the headphones themselves, they generally use electromagnetic effects to move a surface back and forth in sync with the amplifier's current fluctuations. In most cases, the amplifier's current is sent through a coil of wire that's immersed in a strong magnetic field and attached to a movable surface. This current experiences a Lorentz force due to the magnetic field, and that force drives the current, coil, and surface back and forth as the current fluctuates. The moving surface alternately compresses and rarefies the air, thereby reproducing the original sound. The electric power in the circuit becomes sound power for your ears.

Check Your Understanding #6: **Sound Control**

When you connect a microphone to the input of a MOSFET-based amplifier, the microphone sends current back and forth through the input wires. As a result, charge moves onto or off what critical control element in the amplifier?

Answer: The critical control element is the gate of a MOSFET.

Why: In all likelihood, the input current adds or removes charges from the gate of a MOSFET in the amplifier's first stage of amplification.

Epilogue for Chapter 12

In this chapter we looked at two electronic devices to see how they use electricity and magnetism to perform useful tasks. In *power adapters*, we saw how a transformer, diodes, and a capacitor are combined into a system that obtains power from high-voltage alternating

current and uses it to provide low-voltage direct current power. We saw how quantum physics determines the properties of metals, insulators, and semiconductors, and we learned how semiconductor diodes limit current flow to only one direction.

In *audio players*, we studied the ways in which sound information can be represented and looked at the electronic techniques used to represent that sound in digital and analog forms. We also examined the most important modern electronic component: the transistor, a semiconductor device that allows the current in one circuit to control the current in another circuit. We saw how an audio player use transistors and other electronic components in both its digital computer and its analog amplifier.

Explanation: Building an Electronic Kit

Depending on what was included in your kit, you may have worked with resistors, capacitors, diodes, and transistors. The resistors limit currents or produce voltage drops proportional to the currents they carry. The capacitors store charge and energy, or assist currents in flowing between portions of the kit that have different voltages. The diodes limit the directions of current flow, produce fixed voltage drops (typically 0.6 V) in currents, or emit light. The transistors perform a wide variety of tasks, most often letting the current or charge in one circuit control the current or charge in another circuit. You may also have encountered integrated circuits, complex components that contain preassembled collections of transistors and other simpler components.

While assembling the kit, you inserted the components into the printed circuit board and completed the electrical connections using solder. It was important to install the components in the proper orientations because some of them, particularly diodes and transistors, are not symmetric. If you worked with any MOSFETs, you had to be careful about static electricity because the gate insulation is easily destroyed by errant charge. As you melted the solder into place, it was important to avoid overheating the components, particularly those involving semiconductors, because they may have delicate electronic and electrochemical properties that can be destroyed by excessive temperatures.

Chapter Summary

How Power Adapters Work: A power adapter uses a transformer to convey power from an electrical outlet's relatively high-voltage alternating current to the relatively low-voltage alternating current in its secondary coil. The secondary coil's current flows through a set of semiconductor diodes, which act as switches to direct that current out of the adapter through its positive power wire and back to the coil through its negative power wire. The adapter uses a capacitor to store charge and energy, thereby reducing the fluctuations in voltage rise caused by the original alternating power source. The result is a unit that operates from high-voltage alternating current and provides low-voltage direct current.

Simpler adapters omit the capacitor and perhaps even some of the diodes, while more sophisticated adapters include complicated electronic systems to regulate and control their output voltages and currents and to allow them to operate from a broader range of input voltages.

How Audio Players Work: An audio player combines a computer and an audio amplifier into a single unit. The player's computer stores and retrieves the sound information in digital form, with each air pressure measurement represented by a collection of binary bits. These bits can take only values of 0 or 1. For long-term storage, the player places its digital sound information in flash memory and/or magnetic disk memory. For temporary storage while playing a song or working on its song collection, it uses dynamic memory.

After the player's computer has manipulated that information digitally, using logic elements built primarily from MOSFETs, it passes the digital information to a digital-to-analog converter, and that information then takes analog form. This analog signal represents sound as a current that's proportional to the sound's shift in air pressure away from atmospheric pressure.

The analog sound signal enters the input circuit of the player's audio amplifier, which makes use of MOSFETs. This amplifier uses power obtained from the battery to produce an output signal that represents the same sound but with increased voltage and current. This amplified output signal has enough power to produce loud sound in the headphones.

Exercises

1. If a very small piece of material contains only 10,000 electrons and those electrons have as little energy as possible, how many different levels do they occupy in that material?

2. If electrons had four different internal states that could be distinguished from one another, how many electrons could occupy the same level without violating the Pauli exclusion principle?

3. If electrons were not Fermi particles, any number of them could occupy a particular level. How would these electrons tend to arrange themselves among the levels in an object?

4. If electrons were not Fermi particles (Exercise 3), would there still be a distinction between metals and insulators? Explain your answer.

5. Thermal energy can shift some of the electrons in a hot semiconductor from valence levels to conduction levels. What effect do these shifts have on the semiconductor's ability to conduct electricity?

6. Why do semiconductor devices often self-destruct when they are overheated?

7. Is the p-type half of a p-n junction electrically neutral, positive, or negative?

8. In which direction does the electric field point in the middle of a p-n junction?

9. Two capacitors are identical except that one has a thinner insulating layer than the other. If the two capacitors are storing the same amount of separated electric charge, which one will have the larger voltage difference between its plates?

10. Dynamic memory stores bits as the presence or absence of separated charge on tiny capacitors. It takes energy to produce separated charge, and a computer that minimizes this energy will use less electric power. Why does making the insulating layers of the memory capacitors very thin reduce the energy it takes to store each bit in them?

11. Suppose that a battery is transferring positive charges from one plate of a capacitor to the other. Why does the work that the battery does in transferring a charge increase slightly with every transfer?

12. A charged capacitor resembles a battery in that both can supply electric power. However, as the capacitor delivers its power, the voltage of the current it provides decreases. Why?

13. We combine the three decimal digits 6, 3, and 1 to form 631 in order to represent the number *631*. What does the 6 in 631 mean? What are there 6 of?

14. We combine the three binary bits 1, 0, and 1 to form 101 in order to represent the number *5*. What does the leftmost 1 in 101 mean? What is there *1* of?