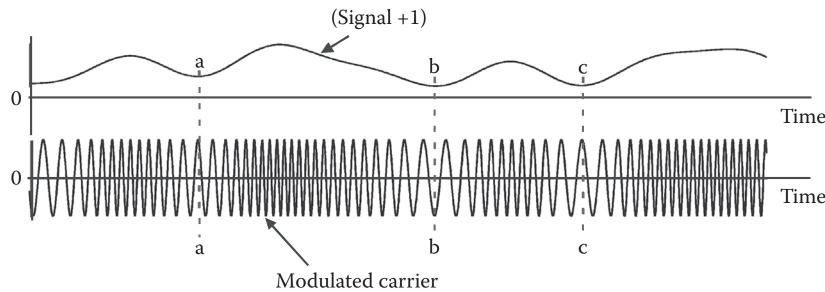

FIGURE 8.8 Frequency modulation (FM). The upper graph is an audio signal, after being shifted by a constant value 1. The lower graph shows a carrier wave whose frequency is varied in accordance with the signal wave.

Instead of broadcasting using AM techniques, radio can be broadcast using FM, as illustrated in **Figure 8.8**. The instantaneous frequency of the carrier is varied, or modulated, according to the value of the signal at each instant. Times labeled *a*, *b*, and *c* are times when the carrier frequency is smallest, making the carrier oscillations slower at those times. For FM radio, the carrier frequency is much higher (88–108 MHz) than for AM radio (520–1610 kHz). Broadcasting and receiving FM transmissions takes place as shown in Figure 8.4, although a different kind of recovery circuit must be used. A major difference is that AM is restricted by the Federal Communications Commission[1] to a frequency range with total bandwidth equal to 1090 kHz (i.e., 520 to 1610 kHz), whereas FM has a much wider range, 88 to 108 MHz, with a much larger total bandwidth, 20 MHz. We will see below that this larger bandwidth gives FM much better fidelity for sound reproduction.

8.3 BASICS OF DIGITAL RADIO

The modern alternative to analog radio is digital radio, in which computers pass digital signals between one another. Computers "speak" to each other using a simple set of symbols, or alphabet. This alphabet, called binary, consists of only two characters, as we discussed in Chapter 2. We could call the two used characters *A* and *B*, or we could call them ☺ and ☹. It really does not matter. Computers use as their two characters *one* (1) and *zero* (0).

A nice illustration of the difference between analog and digital representations of music is shown in **Figure 8.9**. The magnified photograph of the surface of a typical vinyl LP (long-playing) recording disc shows continuously varying tracks in which the playback needle moves, creating an analogy of the original sound wave. The magnified photograph of the surface of a typical compact disc, or CD, shows a binary representation of the strength of the sound wave.

How does digital radio work? As shown in **Figure 8.10**, when a person, say Alice, speaks into a microphone, an analog voltage is produced in the wire. This voltage goes to Alice's computer, where an electronic circuit converts it into a list of *ones* and *zeros*; that is, binary data. A *one* is represented by a higher voltage (e.g., 9 V), whereas a *zero* is represented by a lower voltage (e.g., 0 V). These data are transmitted across a network of computers and are received by Bob's computer, where the *ones* and *zeros* are converted back to a continuous analog voltage, which drives Bob's loudspeaker.

The process of converting a continuously varying voltage or signal into discrete values is called signal sampling. Say the voltage from the microphone varies in time

[1] The Federal Communications Commission (FCC) is a United States government agency. The FCC is charged with regulating interstate and international communications by radio, television, wire, satellite, and cable.

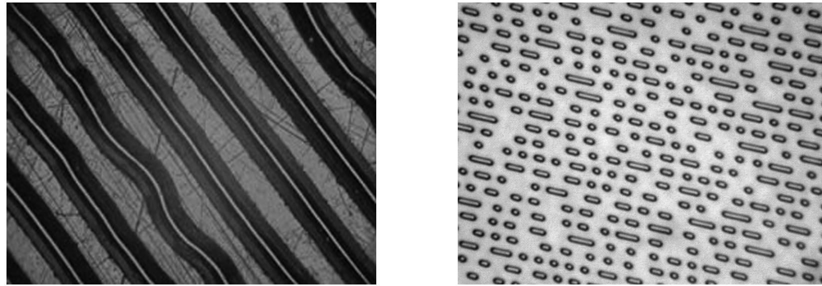

FIGURE 8.9 Music on a vinyl record (left) is represented as an analog signal, in which the shape of the grooves is analogous to the displacement of the recorded sound wave. Music on a CD (right) is represented as a binary signal, in which each bit value is represented by a flat spot or a pit on the CD surface. (Vinyl photo courtesy of Carl Haber, Lawrence Berkeley National Laboratories. CD photo courtesy of Jerry Gleason, University of Oregon.)

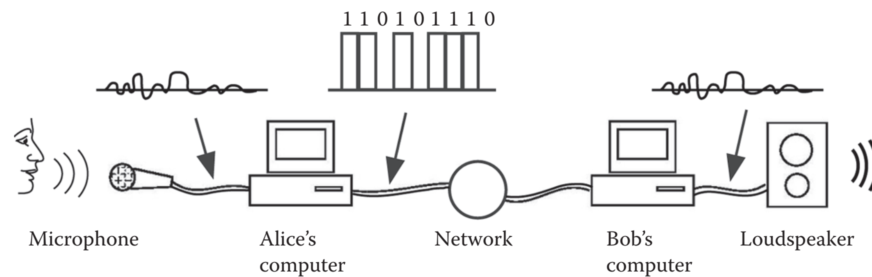

FIGURE 8.10 Internet radio. Each connection shown here is a pair of wires.

as shown in **Figure 8.11**. Such a variation might come from a person whistling a pure musical tone into the microphone. The air near the person's mouth vibrates smoothly in time, causing the air pressure to vary similarly. This causes the voltage to vary in much the same way. An electronic circuit inside Alice's computer samples the value of the voltage (the number on the vertical axis in the graph) at many successive points in time, as shown in the lower part of the figure. ***Sampling*** means measuring something at a series of discrete times and recording the values as a list of numbers. Using sampling, we can represent the signal in Figure 8.11 by a list of numbers; for example,

10, 9, 8, 5, 3, 1, 0, 1, 2, 5, 7, 9, 10, 9, 8, 5, 3, 1, 0, 0, 2, 4, 7, 9, 10, 10, 8, 6, 3, 1.

In this example, the sampled values were rounded off to the nearest whole number. The more precise that the measuring system is, the more digits the numbers will have. For example, 10.0, 9.3, and 7.6, have higher precision than do 10, 9, and 8. The idea of precision was discussed in Chapter 2. Using these rounded sampled values, the signal is represented by the series of points shown in **Figure 8.12**. In general, some information is lost in the sampling process, leading to a distorted version of the signal, seen in the fact that the points do not match up precisely with the original curve.

We can represent the above list of voltage samples (the decimal numbers 10, 9, 8, 5, 3, 1, 0, 1, 2, 5, 7, 9, 10, etc.) using binary representation. Let us agree to use four bits for each number, so the list becomes:

1010, 1001, 1000, 0101, 0011, 0001, 0000, 0001, 0010, 0101, 0111, 1001, 1010, etc.

The computer needs to "know" that it is dealing with decimal whole numbers (no digits to the right of a decimal point) and that these are being represented by 4-bit numbers.

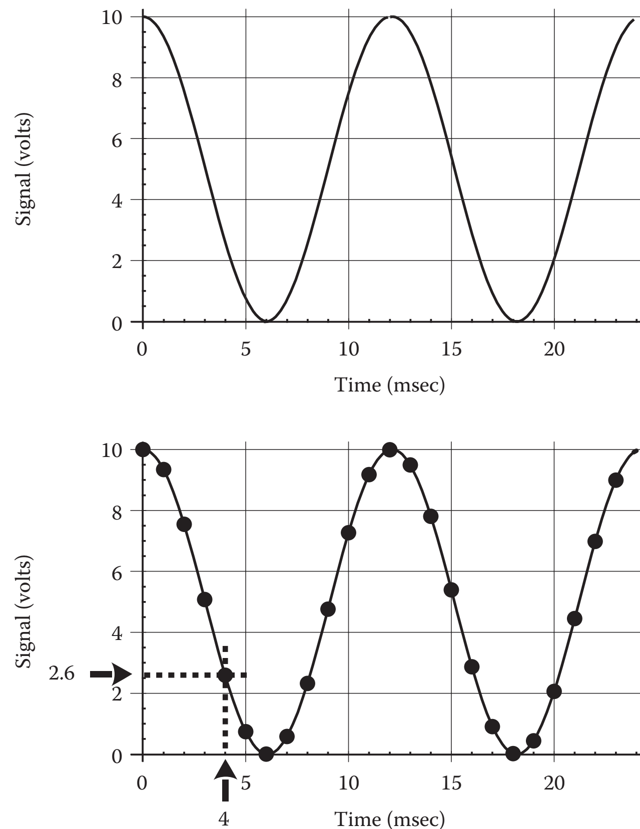

FIGURE 8.11 A voltage varying in time, and the same signal showing the sampled values at time intervals of 1 msec. For example, when the time equals 4 msec, the voltage equals 2.6 V, as indicated by the arrows.

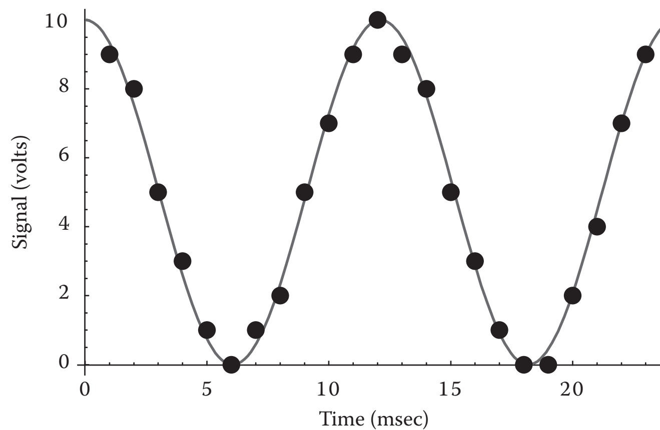

FIGURE 8.12 A graph showing the samples (indicated by dots) that the computer stores and uses to represent the original smoothly varying voltage.

The computer also needs to know that the list starts at a certain time. This set of rules is an example of a ***protocol***.

A ***protocol*** is a set of rules for interpreting a list of binary numbers. The protocol specifies the starting digit, the number of bits per number, whether the number is a whole or fractional number, the voltage values to be used to represent each bit value, error correction scheme, etc.

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Given that the sender and receiver agree on this protocol, we can omit the commas and spaces and write the binary data as:

1010100110000101001100010000000100100101011110011010, etc.

Now we have constructed a list of solely ones and zeros that represents the original voltage signal in **Figure 8.11**.

THINK AGAIN

When a computer records a set of sample values, such as those plotted as points in Figure 8.12, it does not know anything else about the signal. It does not know if the actual signal is a smoothly varying signal like the gray line in Figure 8.12, or a kinky-looking signal, such as would be obtained by connecting the points in the figure by straight lines.

How does Alice's computer send these *ones* and *zeros* to Bob's computer? This is part of a more general, very important, question: How can we represent abstract, mathematical concepts like *zero* or *one* by something in the physical world? In Chapter 2, we discussed using our fingers; those are certainly physical things. They are convenient for representing digital information. Computers use discrete voltage levels as their "fingers" for counting. Recall that the word *digit* means *finger*. To represent binary numbers, computers need to use only two different voltages. Any two values would do. Let us adopt the convention that a *zero* is represented by zero volts (0 V), and a *one* is represented by nine volts (9 V). More generally, we could call these two voltage values "low" and "high." Furthermore, the actual voltage values do not need to be extremely accurate—any voltage close in value to 9 V (e.g., 9.1 V) will be recognized as a *one*, and any voltage near 0 V (e.g., 0.2 V) will be recognized as a *zero*. This insensitivity to precise voltage values leads to the robustness of digital systems, which makes them less prone to making data errors. The designation of voltage ranges for the two bit values must also be part of the protocol.

An illustration of a system for sending digital information between computers is shown in **Figure 8.13**, which shows a telegraph-like technique. A 9-V battery is connected to a switch (a momentary push-ON switch, which snaps back open when not being pressed), and a twisted pair of plastic-insulated wires that travel to the receiving station. Twisted pairs of wires are used to avoid the wires acting as an antenna. Recall from Chapter 5 that an open current loop acts as an antenna when magnetic field lines penetrate the loop. In contrast, a tightly twisted pair has no open loop for magnetic fields to penetrate. Each time the switch is pressed closed, the wire pair has 9 V applied across it. This voltage is relayed to the distant electronic circuit labeled "memory."

The sequence of low and high voltages used to send the first numbers making up the original signal in the above example is shown in **Figure 8.14**. Bob's computer

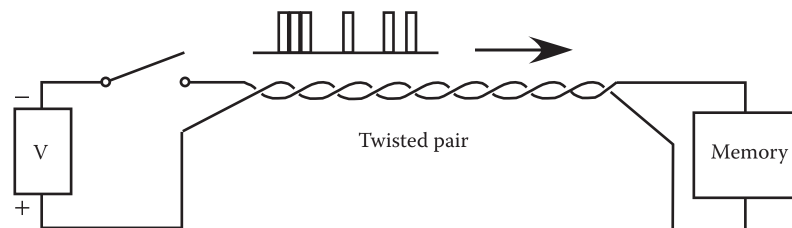

FIGURE 8.13 A telegraph-like system for sending digital information.

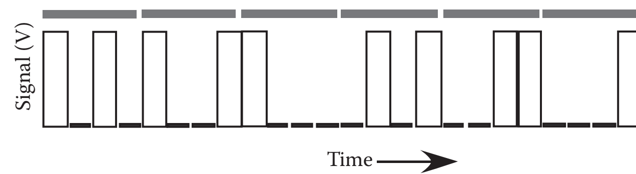

FIGURE 8.14 Twenty-four bits, or *ones* and *zeros*, represented by high (9 V) and low (0.1 V), corresponding to the first six numbers in the sampled signal. Each group of four bits (indicated by horizontal gray bars) corresponds to a number in the range 0 to 9. The horizontal axis is time.

QUICK QUESTION 8.1

Using the same 4-bit protocol as in the above example, draw the voltage sequence representing the four base-ten numbers 2, 4, 0, 9, following the format in Figure 8.14.

will receive the *ones* and *zeros* by measuring the voltage at each pre-assigned time in the series, and will then use the agreed-upon protocol to decode the information. You should check for yourself that the sequence of bits shown in the figure correctly represents the first six numbers in the original sequence in our above example.

Next, Alice's computer transmits the list of bits representing the sampled numbers to Bob's computer. Bob's computer reconstructs the original analog voltage signal and sends this voltage signal to a loudspeaker, which generates a replica of the original sound waves.

The telegraph-like technique shown in Figure 8.13 does not use any carrier wave, and therefore this signal cannot be transmitted as a radio wave through air. Recall that to generate radio waves, you need to oscillate electric charges in an antenna at a radio frequency, for example, 520 kHz. Often we want to send digital data in wireless form; for example, to operate cell phones or wireless Internet connections. We can do this, as with analog radio, by using AM. Text or voice messages being sent to different cell phones are distinguished by their carrier frequencies. To prevent these digital transmissions from interfering with music radio broadcasts, carrier frequencies outside of the AM and FM bands are used for cell phones and wireless Internet. Carriers around 900 MHz are commonly used for cell phones, and carriers around 2,500 and 5,000 MHz are used for wireless Internet (WiFi).

In **Figure 8.15**, a radio-frequency carrier wave is modulated by a sequence of binary data, labeled as the signal voltage. The duration of each data pulse is called the ***data period***, which we denote by T_D. A smaller data period allows us to send more bits per second. That is, the rate of transmitting data, or ***data rate***, becomes larger. In general, the data rate equals the inverse of the data period, that is:

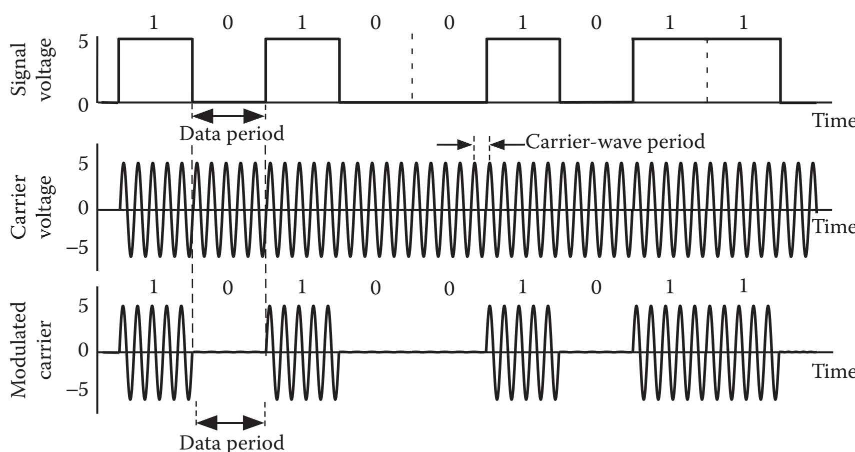

FIGURE 8.15 A binary data list (top) is impressed onto a radio-frequency carrier wave (middle), to create the digital-modulated carrier wave (bottom). In this example, the data period is 5 times larger than the carrier-wave period, meaning that five carrier oscillations occur within each data pulse.

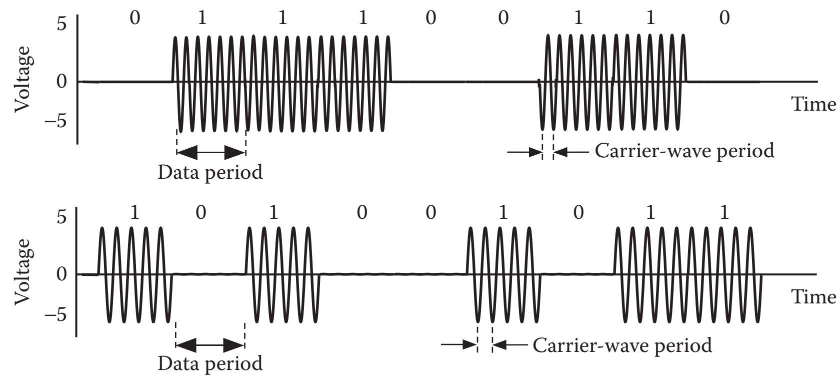

FIGURE 8.16 Two binary data streams, impressed on two carrier waves with distinct frequencies, can be distinguished by a receiver.

$$data\ rate = \frac{1}{data\ period} = \frac{1}{T_D}$$

The carrier wave is shown in the middle graph and has a period equal to $T = 1/f$, where f is the carrier-wave frequency. Notice that the carrier period is smaller than the data period. When the data pulse sequence is multiplied by the carrier wave, the modulated carrier wave shown in the bottom graph is created. This is the radio signal that is broadcast by the antenna. It contains two types of information: the data sequence and the identity of the carrier, which is determined by its frequency.

As an example, if the duration of the data pulses is 1/1000 of a second (sec), or 0.001 sec, then in a time of 1 sec you can send 1,000 pulses. The data rate is then 1,000 pulses/sec, which we could also state as 1,000 Hz or 1,000 bits per second (bps), or 1,000 bps. It is common to use the term ***baud*** to mean 1 bps, after French engineer J. B. F. Baudot. For example, if a phone modem has a data rate of 52,000 bps, we say this rate equals 52 kbaud.

To emphasize the idea of frequency multiplexing for digital channels, **Figure 8.16** shows two modulated carriers, each with a distinct carrier frequency and different binary data being transmitted. Both waves can be present in the same medium, as long as the receiver has the ability to select one frequency channel for reception.

We summarize as follows:

Digital broadcast radio uses a high-frequency carrier wave, the amplitude of which is modulated to represent the binary-number sequence corresponding to the sampled voltages in the signal it is transmitting.

8.4 THE PRINCIPLE OF CARRIER MODULATION

An important question is: How rapidly can we transmit data through a medium? That is, how fast can we modulate a carrier wave with a stream of data, whether it is analog or digital? The answer depends on an important principle:

Principle of carrier modulation: We cannot modulate a carrier wave at a frequency higher than the frequency of the carrier, without destroying the identity of that carrier.