Chapter 4

Signals

We are all familiar with signals of many kinds. Smoke can signal the results of a papal election. A wink of an eye, a pat on the back, a gentle touch, and a handshake are some of the ways we communicate through signals. But the term *signals* has a more technical meaning when applied to communication systems.

What is a signal? A signal is an event that changes with time and can be used to convey information as a means to facilitate communication. Signals exist in a variety of media and modalities, such as in sound, electricity, electromagnetism, and light. Radio waves, telephone speech, and the electrical currents flowing in a personal computer are all signals. This chapter describes how we can characterize signals in general terms. The chapters in Parts II, III, and IV examine the specific signals of television, computers, and telephone service.

Waveforms

Engineers are always drawing pictures; they seem to need a pencil to think. But graphic images are the way engineers depict concepts, electrical circuits, data, and signals. A signal varies with time and can be depicted graphically to show how the signal looks as a function of time. Time is plotted along the horizontal axis (the x-axis). The amplitude of the signal at each and every instant of time—called the instantaneous amplitude—is plotted along the vertical axis (the y-axis). The instantaneous amplitude might represent sound pressure, light energy, or electrical voltage.

The shape of the graphical representation of a signal is called the waveshape, or waveform, of the signal. Engineers use electronic devices called oscilloscopes to look at waveforms. Because the waveform is a representation of how a signal varies with respect to time, the representation is called a time-domain representation of the signal.

A waveform that has a basic shape that keeps repeating is called a periodic signal. Certain periodic waveshapes appear so frequently that they have their own identities, as shown in Figure 4.1. A square wave has a basic shape, or period, that is square. A triangular waveform has a triangular basic shape. A sawtooth waveform has a basic shape that looks like the tooth of a saw. Sawtooth waveforms are encountered in television and are the shape of the signals that make the electron beam in the display tube move from the top to the bottom and from left to right.

The length in time of the shortest basic shape of a periodic waveform is called the period of the wave. The period is measured in

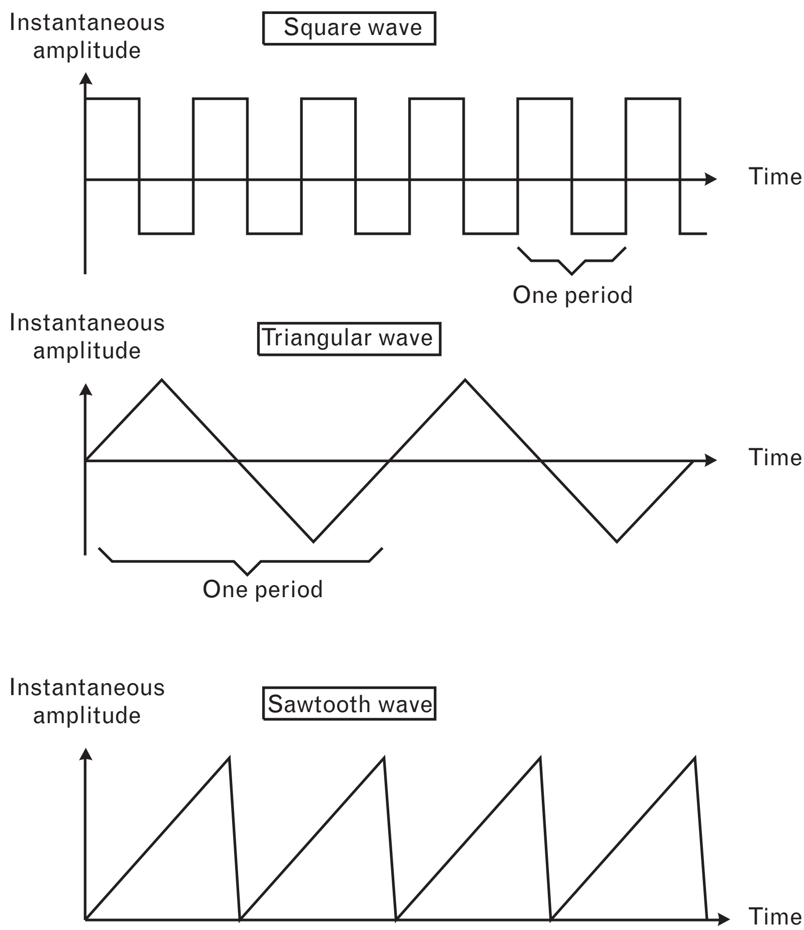


FIGURE 4.1 *A periodic waveform has a basic shape that repeats continuously. The shortest basic shape is called the period of the wave.*

seconds. One full period completes a full cycle as it returns to repeat itself. The rate at which one full period, or basic shape, repeats itself is called the fundamental frequency of the waveform. Frequency is measured in cycles per second, or hertz (abbreviated as Hz). The fundamental frequency and the period of a waveform have a reciprocal relationship. If T is the period in seconds and F is the fundamental frequency in hertz, then $F = 1/T$ and $T = 1/F$.

The concept of wavelength was introduced in Chapter 3. Radio engineers are concerned with the design of radio antennas. The length of a radio antenna is related to the wavelength of the radio waves to be received. For that reason, radio engineers frequently use wavelength rather than frequency when specifying radio signals. The wavelength is related to frequency by the expression $\lambda = v/F$, where λ (lambda) is the wavelength, v is the velocity of the wave, and F is the frequency. For radio waves, v is the speed of light, which is about 3×10^8 meters per second (or 186,000 miles per second). A radio wave at a frequency of 900 million Hz would have a wavelength of 0.3m, or about 1 ft.

Engineering Notation

Very large and very small numbers are encountered in the worlds of science and technology. A shorthand notation is needed to represent such numbers and to indicate their magnitude. Engineering notation does that by representing numbers as powers of 10. Table 4.1 summarizes the notation used to represent big numbers and small numbers.

Consider a frequency of 1,260,000 Hz. Using engineering notation, that frequency would be written as 1.26 MHz. The shorthand form is obtained by expressing 1,260,000 as 1.26×10^6 and then using the *mega* prefix (abbreviated as M) to represent 10^6. The same methodology is used for small quantities. A period of 0.005 second is written as 5 ms, obtained by writing the number as 5×10^{-3} and then substituting the *milli* prefix for 10^{-3}.

Sine Waves

A tuning fork when struck produces an almost pure tone with no harmonics or overtones. A pure tone at a single frequency is called a sine wave (Figure 4.2). Sine waves are important because they are the

Table 4.1 Engineering notation

	Number	Notation	Prefix
Big	1,000,000,000,000	10^{12}	tera (T)
	1,000,000,000	10^{9}	giga (G)
	1,000,000	10^{6}	mega (M)
	1,000	10^{3}	kilo (k)
	1	0^{0}	
Small	0.001	10^{-3}	milli (m)
	0.000001	10^{-6}	micro (μ)
	0.000000001	10^{-9}	nano (n)
	0.000000000001	10^{-12}	pico (p)

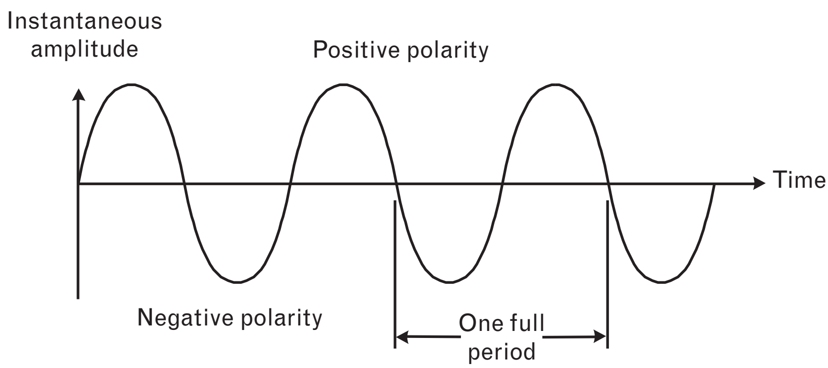


Figure 4.2 *The sine wave is a periodic signal with a smoothly varying shape. A sine wave has values in the positive direction, called the positive polarity, and values in the negative direction, called the negative polarity. The sine wave is the basic building wave of more complex waveforms.*

fundamental building blocks from which more complex signals can be created. Sine waves can also be used as a way to move other signals to different frequency ranges, a process called modulation.

A sine wave is so named because it can be created as the y-axis projection of a point on a rotating circle, as shown in Figure 4.3. From trigonometry, we know that the y-axis projection of a right triangle is the hypotenuse multiplied by the sine of the angle, thus the term *sine wave*.

A sine wave has a maximum amplitude and a frequency, or a period (remember that the frequency is the reciprocal of the period). A sine wave as a function of time normally begins at zero time ($t = 0$) and at zero amplitude, increasing in a positive direction. A normal sine wave can be shifted to the left or to the right, so that it begins ($t = 0$) in some other way. That is called the phase, or phase shift, of the sine wave. A

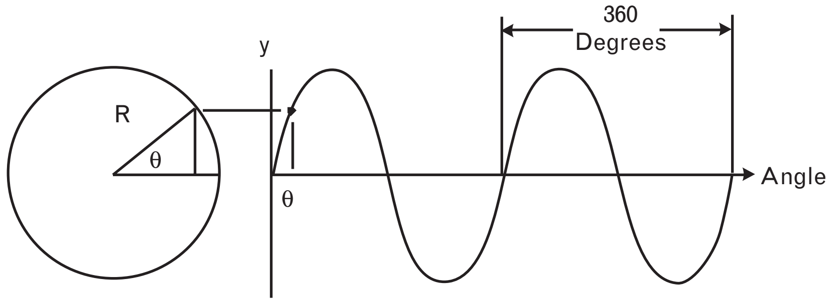


Figure 4.3 *A sine wave is generated as the y-axis projection of a point on a circle that is rotating in a counter-clockwise direction. The y-axis projection equals the radius multiplied by the sine of the angle through which the point has rotated.*

sine wave is uniquely defined by its maximum amplitude, its frequency (or alternatively, its period), and its phase (Figure 4.4). Once those three quantities are known, the exact shape of the sine wave has been specified for all time.

Fourier Analysis and Synthesis

The use of a series of sine waves to represent any periodic waveshape was discovered by the French physicist Jean Baptiste Joseph Fourier early in the nineteenth century. He showed mathematically that any periodic waveform could be represented as the sum of sine waves with the appropriate maximum amplitudes, frequencies, and phases. The method of Fourier analysis and synthesis is named after him.

The graphical example shown in Figure 4.5. might help your understanding of Fourier synthesis. We start with a sine wave at some

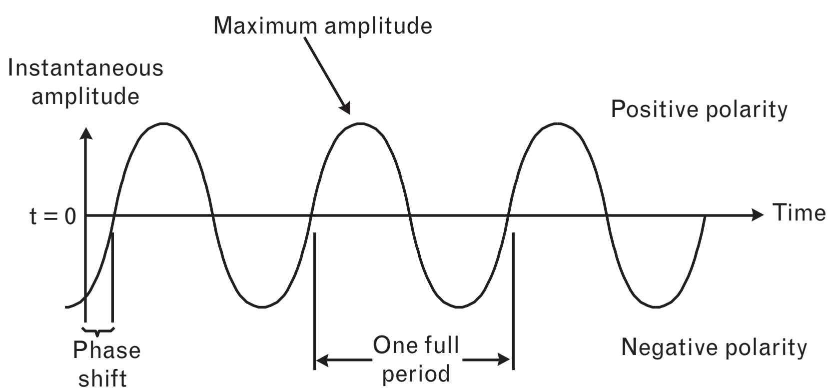


Figure 4.4 *The precise shape of a sine wave is uniquely defined by its maximum amplitude, its frequency (or alternatively, its period), and its phase.*

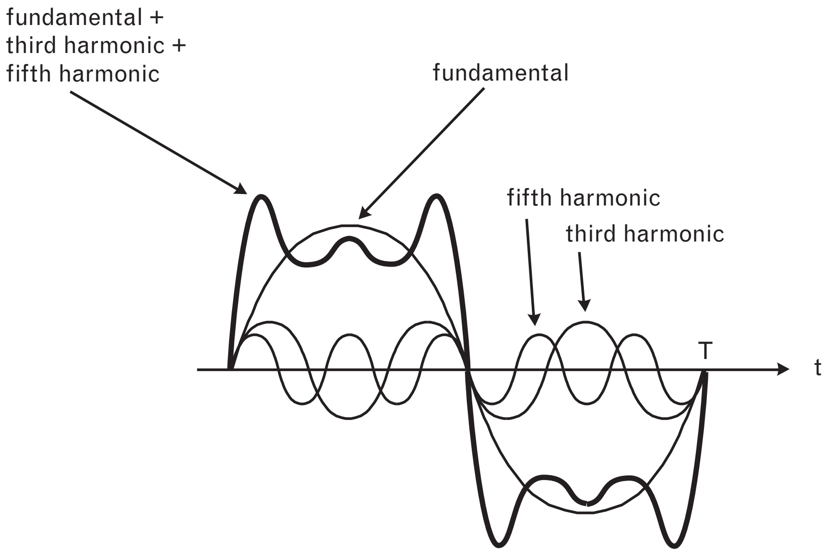


FIGURE 4.5 *Three sine waves are added together at each instant of time to create a new waveform. The second sine wave has a frequency three times that of the first and a maximum amplitude one-third that of the first. The third sine wave has a frequency five times that of the first and a maximum amplitude one-fifth that of the first. As sine waves at higher harmonics are added, the resulting wave looks more and more like a square wave.*

fundamental frequency *F*. Next we add to it a second sine wave at a frequency of 3*F* and with a maximum amplitude one-third that of the fundamental. The third harmonic pulls down the positive and negative peaks of the fundamental, and the resulting waveform starts to look somewhat like a square wave. Next we add in a fifth harmonic at a frequency of 5*F* and with a maximum amplitude one-fifth that of the fundamental. That squares off the corners even more, making the result more like a square wave. The process would continue adding more odd harmonics with maximum amplitudes inversely proportional to the harmonic number. Ultimately, a perfect square wave would result, except at the sudden discontinuities of the corners, where the mathematics fails—an effect called the Gibbs phenomenon.

Fourier analysis can be applied to any waveform to determine the exact harmonic frequencies that are needed, along with the corresponding maximum amplitudes and phases to recreate, or synthesize, any periodic signal.

Spectrum

Consider a sine wave at some frequency *F* and maximum amplitude *A*. Assume it has no phase shift for the time being. We can draw the waveform precisely as a function of time. But that is boring to do because we now all know what a sine wave looks like. What is interesting about a sine wave is its exact frequency and corresponding maximum amplitude—we know what it looks like. It is the frequency and the amplitude of a sine wave that distinguish it from other sine waves. This suggests that we create a graph showing the maximum amplitude *A* of the sine wave along the y-axis and its frequency *F* along the x-axis (Figure 4.6). In such a graph, a single sine wave would be depicted for our example as a single point, or line, at frequency *F* and maximum amplitude *A*.

This representation of the frequency and the maximum amplitude of a sine wave is called the spectrum of the sine wave. From the principle of Fourier analysis and synthesis, we know that any waveform can be represented as the sum of a number of sine waves. Thus, the spectrum of any waveform depicts the various frequency components, along with their corresponding maximum amplitudes. The time domain shows the actual waveform. The frequency domain shows the maximum amplitudes of the various sinusoidal components of the waveform.

A periodic signal has a spectrum that consists only of frequency components at harmonic multiples of the fundamental. A perfectly periodic signal does not exist in the real world, because it would have to continue for all time into the future. Real signals are more complex and terminate after some time. Some are periodic in only a short time interval. Others have no repetitive pattern at all. Real signals have spectra that are smooth with many frequency components.

Bandwidth

Most signals occupy only a finite range of frequencies. The width of the range of frequencies is called the bandwidth of the signal, as shown in

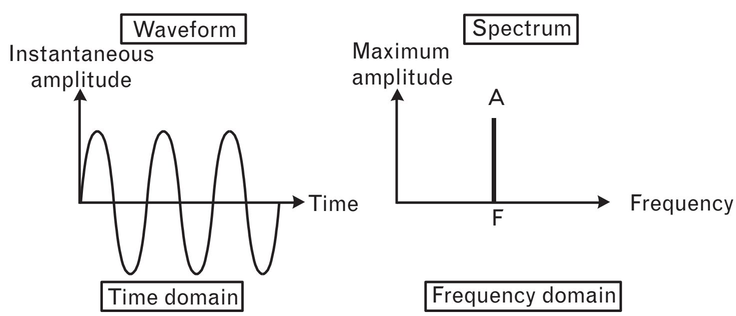


FIGURE 4.6 *We can represent a sine wave graphically in the time domain by drawing its actual shape. Alternatively, we can represent it in the frequency domain as a line at its frequency and maximum amplitude.*

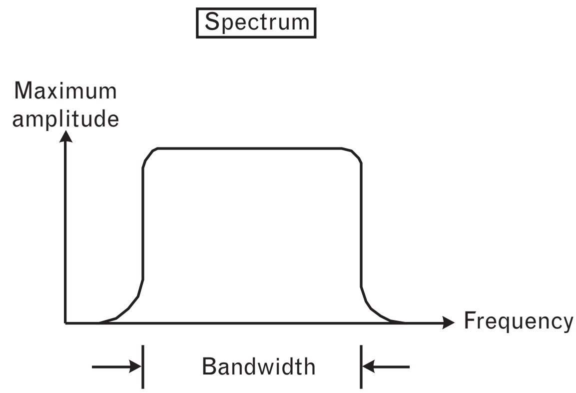


Figure 4.7 *Communication signals occupy only a finite range of frequencies. That range is called the bandwidth of a signal.*

Figure 4.7. Communication systems and channels do not allow all frequencies to pass through, so they, too, have a bandwidth of signals that they pass.

Table 4.2 lists the bandwidths for a variety of different signals and communication channels.

Bandwidth is an important measure of a signal or a communication channel. Bandwidth determines the capacity of a communication channel to carry signals. Suppose a communication channel has a bandwidth of 28 kHz and is to be used to carry telephone speech signals. Because each telephone speech signal requires 4 kHz, the communication channel could carry only seven speech signals simultaneously. We shall see in Chapter 17 that optical fiber has tremendous bandwidth and considerable capacity to carry thousands of signals.

Sometimes it is necessary to deliberately restrict the bandwidth of a signal. This is accomplished with filters, as shown in Figure 4.8. A low-

Table 4.2 Bandwidths

Signal or channel	Bandwidth
Telephone speech	4 kHz
AM radio station	10 kHz
Hi-fi amplifier	20 kHz
FM radio station	200 kHz
AM radio band	1.2 MHz
TV channel	6 MHz
FM radio band	20 MHz

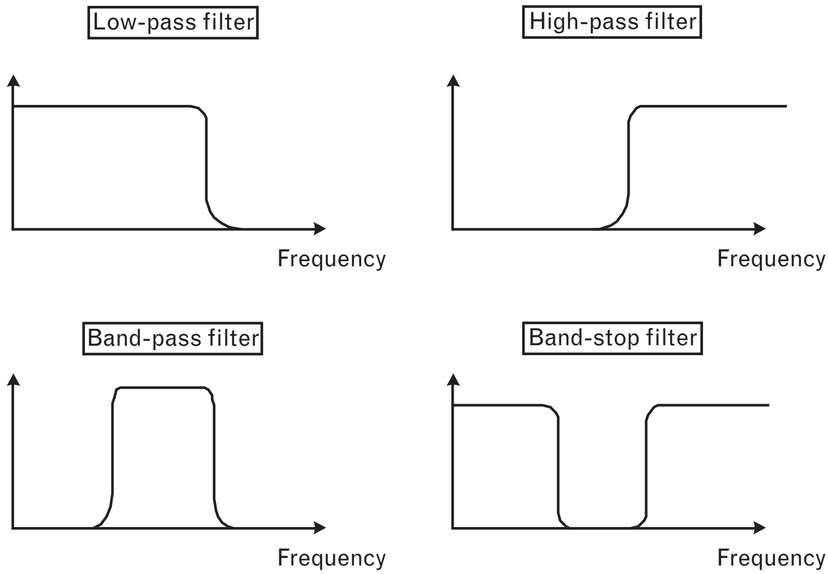
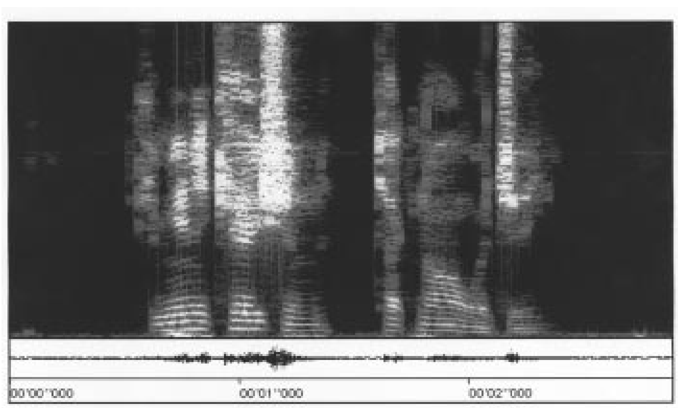


FIGURE 4.8 *Various types of filters can stop certain frequency components from passing, thereby shaping the spectrum of signals.*

pass filter (LPF) allows only the low-frequency components of a signal to pass through. A high-pass filter (HPF) allows only high-frequency components of a signal to pass through. A high-pass filter would be used to protect a high-frequency loudspeaker—called a tweeter—from low frequencies, which would damage it. A filter that allows a band, or



A speech spectrogram, or sonogram, converts speech or sound into a visual representation. This representation shows the spectral composition of the signal, with time along the horizontal axis and frequency along the vertical axis. The brightness of the representation corresponds to the energy in the signal at different times and frequencies. The spectrogram shown here is for the author speaking the words "communication technology."

range, of frequencies to pass through is called a band-pass filter (BPF). A filter that stops a band is called a band-stop filter.

Spectrograms

The sound spectrograph was invented during World War II to display speech signals, to help break enemy speech-scrambling systems, and to analyze underwater signals to help identify enemy submarines. Today, scientists use the sound spectrograph also to analyze bird and whale sounds.

The sound spectrograph generates sound spectrograms that display the changes with time of a signal's spectrum. The spectrogram is an attempt at a three-dimensional representation of a time-changing spectrum. In Figure 4.9, the maximum amplitudes are depicted as the darker displays. The more energy at a particular frequency, the darker the display at that frequency and time. Time is plotted along the horizontal axis and frequency along the vertical axis. For a speech signal, certain patterns appear, such as bands of frequencies that correspond to the resonances in the vocal tract. Two wonderful papers from the 1940s clearly describe the sound spectrograph and its use to display speech signals [1, 2].

Decades ago, controversy clouded the speech community regarding the use of speech spectrograms in court cases. The claim was made that spectrograms—called voiceprints—could be used like fingerprints to identify particular speakers. Actually, variations from speaker to speaker are not distinct enough to allow the use of spectrograms to identify

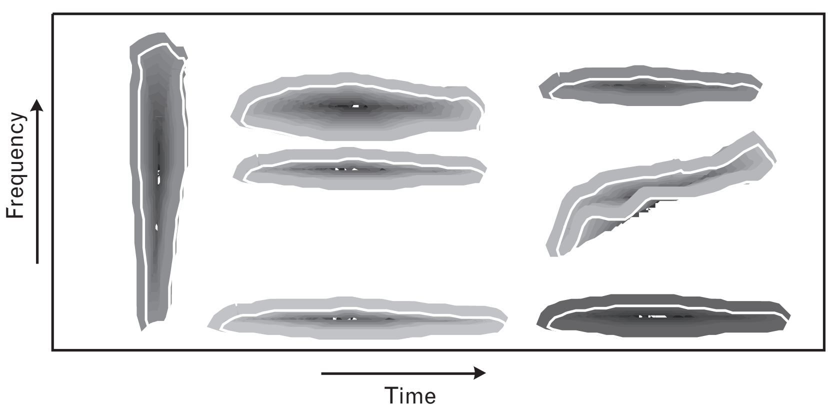


FIGURE 4.9 *A sound spectrogram shows the intensity of different frequency components of a signal as it varies with respect to time. For a speech signal, patterns characteristic of resonances in the vocal tract appear.*

individuals, although spectrograms could be used to eliminate suspects if the differences are great enough.

References

1. Koenig, W., H. K. Dunn, and L. Y. Lacy, "The Sound Spectrograph," *J. Acoustical Society America*, Vol. 17, 1946, pp. 19–49.
2. Steinberg, J. C., and N. R. French, "The Portrayal of Visible Speech," *J. Acoustical Society America*, Vol. 17, 1946, pp. 4–18.

Additional Reading

Pierce, J. R., and A. M. Noll, *Signals: The Science of Telecommunications*, New York: Scientific American Library, 1990.