When an analog signal is applied to an ADC, the ADC evaluates the instantaneous sample of that signal against predefined high and low voltage extremes that define an allowable input range for that ADC. As shown in Fig. 15.1, the ADC overlays a range of numbers between these extremes, thereby dividing the overall voltage range into many small incremental ranges, or *quanta*. A switch is often used to convey the idea of an instantaneous sample being applied to the ADC; the switch is normally open and is closed for a brief instant so that the ADC can measure a voltage. Because of the binary nature of digital systems, practically every ADC divides the allowable input voltage range by some power of two. Each small voltage quantum is mapped to a unique number. The quantum index that most closely matches the observed sample is emitted from the ADC, enabling digital logic to comprehend the instantaneous amplitude of the applied signal as a discrete number. The conceptual example depicts an ADC with voltage extremes of +5 and 0 V and a resolution of 8 bits, indicating that the 5-V range is divided into 256 quanta. Each quantum represents a range of 5 V ÷ 255 = 19.61 mV. A digital sample with the value 0x00 would indicate 0 V, and a sample with value 0xFF would indicate 5 V. If a 0.75 V sample is converted from analog to digital, the sampled value will be either 0x26 (38_{10}) or 0x27 (39_{10}), depending on the rounding mechanism used, because 0.75 V is greater than 38 × 19.61 mV (0.745 V) but less than 39 × 19.61 mV (0.765 V). When an input voltage is presented that is outside the allowable range, the typical ADC returns a saturated sample value of either 0 or $2^N - 1$, depending on whether the input was too low or too high.

Like an ADC, a DAC divides a range of output voltages into many small quanta and operates on the concept of discrete samples in time. At the core of a conceptual DAC is a numerically controlled voltage source that emits a linear range of voltages corresponding to a linear range of discrete numerical samples applied to it. This is illustrated in Fig. 15.2, assuming a voltage source with a minimum output of 0 V and a maximum of V_{OMAX}. The range from 0 to V_{OMAX} is divided by the DAC's resolution, yielding the voltage range of each quantum as in an ADC. Whereas the sampling process in an ADC is modeled using a switch to capture an instantaneous voltage, the similar process in a DAC is modeled with a synchronous register that presents a new sample to the voltage source each sampling interval as regulated by the sample clock. Using the previous example of an 8-bit ADC where 0.75 V would be converted to 0x27, a similar 8-bit DAC could be setup with V_{OMAX} = 5 V. Under these circumstances, the sample value of 0x27 is converted to 0.765 V, because the quantum size remains 19.61 mV.

It is apparent from the preceding discussion that the sampling process is imperfect. The 0.75-V input level is rounded to a multiple of the quantum voltage magnitude, and the resulting digital sample

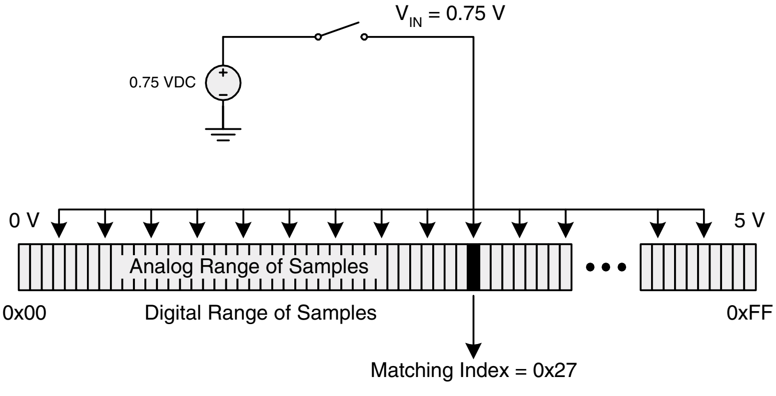

FIGURE 15.1 Conceptual analog-to-digital converter.

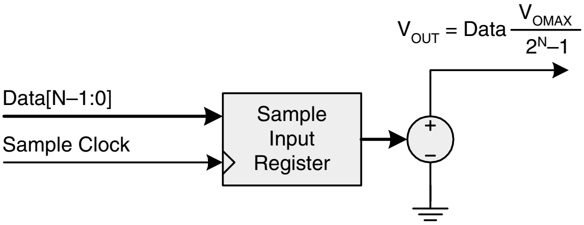

FIGURE 15.2 Conceptual digital-to-analog converter.

is converted back to analog with the rounding made permanent. The exact magnitude of the original analog signal is lost. The process of fitting a continuous analog signal into the closest matching voltage quantum is known as *quantization*. Quantization distorts the signal by skewing the actual voltage to a discrete level. In the preceding example, there would be no discernible difference between 0.75 and 0.76 V, because all allowable voltages are measured to a resolution of 19.61 mV. Quantization errors can be reduced by increasing the resolution of the digital samples. If 12-bit samples were converted instead of only 8 bits, the resolution would improve to $5\text{ V} \div (2^{12} - 1) = 1.22$ mV.

As reality must surely dictate, increased sampling resolution comes at a price. The question becomes how much resolution is required by a particular application. Sensing the temperature in a house for the purpose of controlling a furnace or air conditioner probably does not require more than eight bits of resolution. The useful range of household temperatures to measure may range from 10 to 40°C (50 to 104°F). Even widening this range to between 0 and 50°C (32 and 122 °F) would still provide a resolution of 0.2°C with an 8-bit ADC, plenty for the specified application. However, recording a musical performance with high fidelity may require 12, 16, or more bits of resolution.

Increased sampling resolution does not directly translate to an increase in sampling accuracy. Resolution and accuracy are related but not synonymous. Resolution indicates the granularity of samples, whereas accuracy specifies how reliably the conversion is performed. Accuracy in an ADC indicates how it selects the proper sample to represent the input voltage. For a DAC, accuracy indicates how stable a voltage is generated for each discrete sample. Accuracy is a fairly complex topic, because it involves many aspects of the ADC or DAC circuit, including ambient noise and filtering of that noise. If ±10 mV of noise is present in a 12-bit ADC circuit with 1.22 mV of resolution, the accuracy of the converted samples will be far worse than 1.22 mV, because the noise will randomly skew the voltage up and down as it is sampled. It follows that a well designed 8-bit ADC can provide more useful results than a poorly designed 12-bit ADC.

15.2 SAMPLING RATE AND ALIASING

The rate at which samples are converted is as important as the resolution with which they are converted. How fast should an analog signal be sampled: once per second, one thousand times per second, one million times? The necessary sampling rate is a function of the analog signal's frequency content. Higher frequencies change more rapidly and therefore must be sampled at a faster rate to be measured accurately. Per Fourier analysis, a signal's frequency content is evaluated by representing that signal as a sum of sine waves, each with a unique frequency and phase. The highest frequency sine wave sets the constraint that the sampling rate analysis must take into account.

Consider the 1-kHz sine wave shown in Fig. 15.3 that is being sampled by an ADC at 10 kHz. Each black dot represents a discrete voltage level that is converted into a digital sample. The equally