

- Resolution & Aliasing
- Analog-to-Digital
- Digital-to-Analog

Analog I/O Functionality

Today, digital computers and other microprocessor-based devices have replaced analog recording and display technologies in all but the simplest data acquisition applications. And while computers have had an undeniably positive impact on the practice of data acquisition, they speak only a binary language of ones and zeroes.

(Figure 1-1) for converting analog and digital information about real-world processes and events into the language of computers.

Resolution & Aliasing

Most sensors for measuring temperature, pressure, and other continuous variables provide a continuously varying electrical output to repre-

sented as a digital number, however, this essentially continuous resolution is limited to discrete steps. This resolution of an A/D conversion often is stated in terms of bits—the more bits the finer the resolution. The number of bits determines the number of divisions into which a full-scale input range can be divided to approximate an analog input voltage. For example,

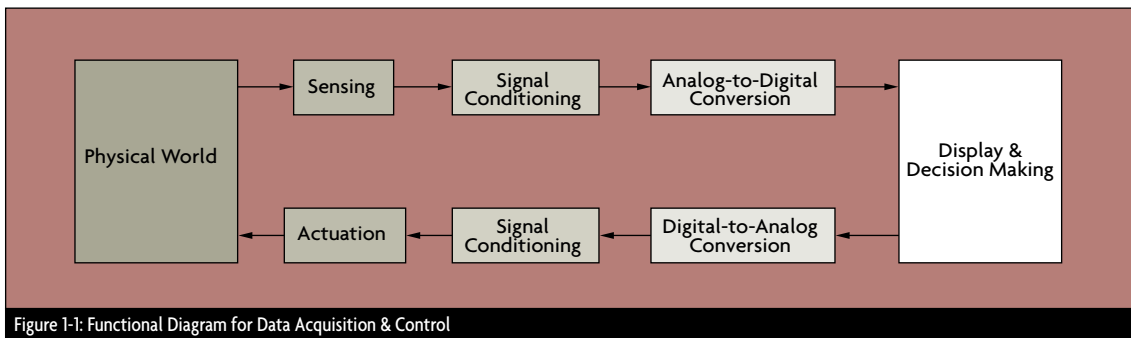


Figure 1-1: Functional Diagram for Data Acquisition & Control

Manufacturing processes and natural phenomena, however, are still by their very nature analog. That is, natural processes tend to vary smoothly over time, not discontinuously changing states from black to white, from on to off.

To be meaningfully recorded or manipulated by a computer then, analog measurements such as pressure, temperature, flow rate, and position must be translated into digital representations. Inherently digital events, too, such as the tripping of a motor or a pulse generated by a positive displacement flowmeter, must be made interpretable as a transistor-to-transistor logic (TTL) level changes in voltage. Hence, the origination and ongoing development of input/output (I/O) systems

sent the magnitude of the variable in question. To make this signal interpretable by a microprocessor, it must be converted from a smooth continuous value to a discrete, digital number (Figure 1-2).

This analog-to-digital (A/D) conversion process poses two primary challenges: one of quantization and one of sampling in time (Figure 1-3). Quantization refers to the uncertainty introduced upon conversion of an analog voltage to a digital number. Measurement transducers or transmitters typically provide continuously varying signals between 0-10 V dc, ±5 V dc, 0-100 mV dc, or 4-20 mA dc. Thermocouples and resistance temperature devices (RTDs) are other common low voltage inputs.

When this analog value is repre-

8-bit resolution of a 0-10 V input signal means that the range is divided into $2^8 = 256$ steps. This yields a step, or interval, size of $10 \text{ V}/256 = 0.039 \text{ V}$. Thus, a 10-V input is equal to the digital number 255 and a 0-V input corresponds to 0. Each 0.039-V change in the input is indicated by adding or subtracting 1 from the previous number. (For example, 9.961 V is digitally represented by 254.)

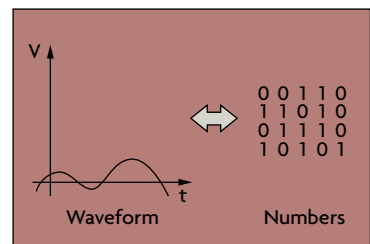
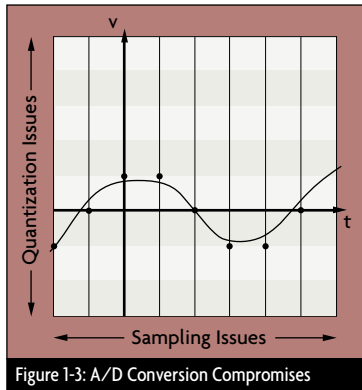


Figure 1-2: The Analog-to-Digital Interface



Digital data acquisition systems not only quantize data in terms of magnitude; time, too, is parceled into discrete intervals (Figure 1-3). In general, there is no information about the behavior of the process between data points gathered. Special precautions, then, must be taken to ensure no meaningful data is lost and interpolation between recorded points remains a valid assumption.

The Nyquist theorem defines the necessary relationship between the highest frequency contained in a signal and the minimum required sampling speed. Nyquist stated that the sample rate must be at least twice the highest frequency component contained within the input signal. So, to sample a 1-Hz sine wave, the sample rate should be at least 2 Hz. (But a rate of 8-16 Hz would be much better for resolving the true shape of the wave.)

The primary implications of ignoring the Nyquist criterion include not only missing high frequency information but of introducing aliasing; if the sample rate is not fast enough, the presence of totally nonexistent frequencies may be indicated (Figure 1-4). It is aliasing that makes a helicopter's rotors or a car's wheels appear to turn slowly backwards when seen in a movie. Low-pass, or

anti-aliasing filters can be used to limit the measured waveform's frequency spectrum so that no detectable component equals or exceeds half of the sampling rate.

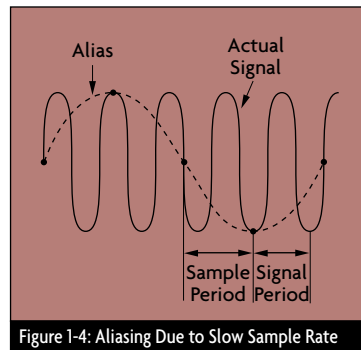
Designing or specifying a device for A/D conversion consists of a series of trade-offs. As will be amply demonstrated in the next section, more resolution (more bits) means more accurate conversion but more expensive hardware. Similarly, slower sample rates mean cheaper A/D conversion, but the Nyquist criterion must still be satisfied.

A/D Conversion

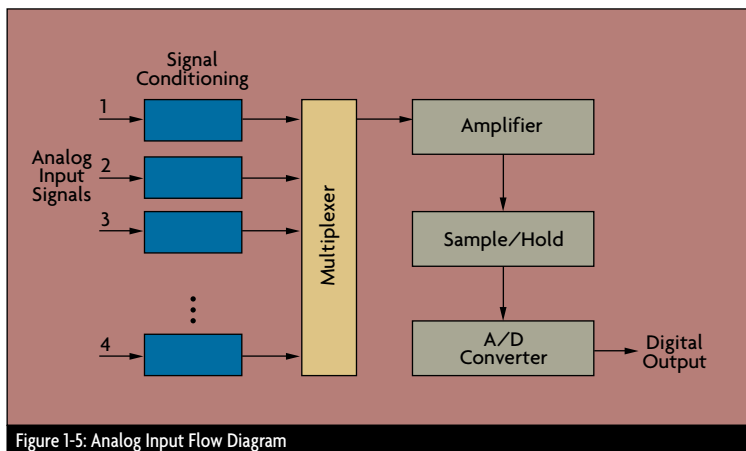
Continuous electrical signals are converted to the digital language of computers using analog-to-digital (A/D) converters. An A/D converter may be housed on a PC board with associated circuitry or in a variety of remote or networked configurations. In addition to the converter itself, sample-and-hold circuits, an amplifier, a multiplexer, timing and synchronization circuits, and signal conditioning elements also may be on board (Figure 1-5). The logic circuits necessary to control the transfer of data to computer memory or to an internal register also are needed.

When determining what type of A/D converter should be used in a given application, performance should be closely matched to the requirements of the analog input transducer(s) in question. Accuracy, signal frequency content, maximum signal level, and dynamic range all should be considered.

Central to the performance of an A/D converter is its resolution, often expressed in bits. An A/D converter



essentially divides the analog input range into 2^N bins, where N is the number of bits. In other words, resolution is a measure of the number of levels used to represent the analog input range and determines the converter's sensitivity to a change in analog input. This is not to be con-



fused with its absolute accuracy! Amplification of the signal, or input gain, can be used to increase the apparent sensitivity if the signal's expected maximum range is less than the input range of the A/D converter. Because higher resolution A/D converters cost more, it is especially important to not buy more resolution than you need—if you have 1% accurate (1 in 100) temperature transducers, a 16-bit (1 in 65,536) A/D converter is probably more resolution than you need.

Absolute accuracy of the A/D conversion is a function of the reference voltage stability (the known voltage to which the unknown voltage is compared) as well as the comparator performance. Overall, it is of limited use to know the accuracy of the A/D converter itself. Accuracy of the system, together with associated multiplexer, amplifier, and other circuitry is typically more meaningful.

The other primary A/D converter performance parameter that must be

the front-end analog circuitry to acquire a signal. Also called aperture time, it is the time for which the converter must see the analog voltage in order to complete a conversion.

for speed, others for economy, and others for a compromise among competing priorities (Figure 1-6). Industrial and lab data acquisition tasks typically require 12 to 16 bits—

Figure 1-6: Alternative A/D Converter Designs

DESIGN	SPEED	RESOLUTION	NOISE IMMUNITY	COST
Successive approximation	Medium	10-16 bits	Poor	Low
Integrating	Slow	12-18 bits	Good	Low
Ramp/counting	Slow	14-24 bits	Good	Medium
Flash/parallel	Fast	4-8 bits	None	High

- **Conversion** is the time needed to produce a digital value corresponding to the analog value.
 - **Transfer** is the time needed to send the digital value to the host computer's memory.
- Throughput, then, equals the number of channels being served divided by the time required to do all three functions.

A/D Converter Options

While all analog-to-digital converters are classified by their resolution or number of bits, how the A/D cir-

12 is the most common. As a rule, increasing resolution results in higher costs and slower conversion speed.

- **Successive approximation:** The most common A/D converter design used for general industrial and laboratory applications is successive approximation (Figure 1-7). This design offers an effective compromise among resolution, speed, and cost. In this type of design, an internal digital-to-analog (D/A) converter and a single comparator—essentially a circuit that determines which of two voltages is higher—are used to narrow in on the unknown voltage by turning bits in the D/A converter on until the voltages match to within the least significant bit. Raw sampling speed for successive approximation converters is in the 50 kHz to 1 MHz range.

To achieve higher sampling speeds, a redundancy technique allows a fast initial approximate conversion, followed by a correction step that adjust the least significant bit after allowing sufficient settling time. The conversion is therefore completed faster at the expense of additional hardware. Redundancy is useful when both high speed and high resolution are desirable.

- **Flash/parallel:** When higher speed operation is required, parallel, or flash-type A/D conversion is called

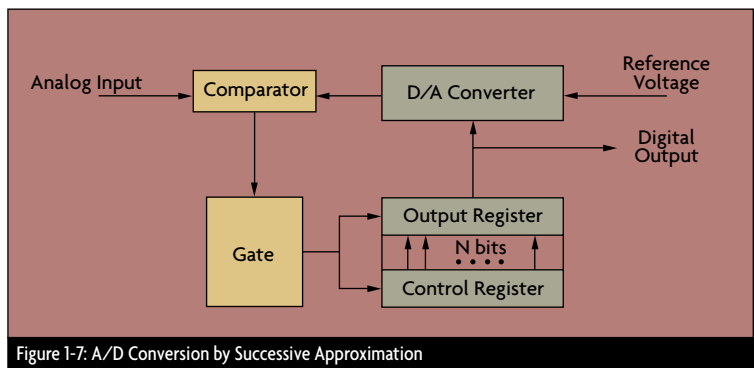


Figure 1-7: A/D Conversion by Successive Approximation

considered is speed—throughput for a multi-channel device. Overall, system speed depends on the conversion time, acquisition time, transfer time, and the number of channels being served by the system:

- **Acquisition** is the time needed by

circuitry achieves this resolution varies from device to device. There are four primary types of A/D converters used for industrial and laboratory applications—successive approximation, flash/parallel, integrating, and ramp/counting. Some are optimized

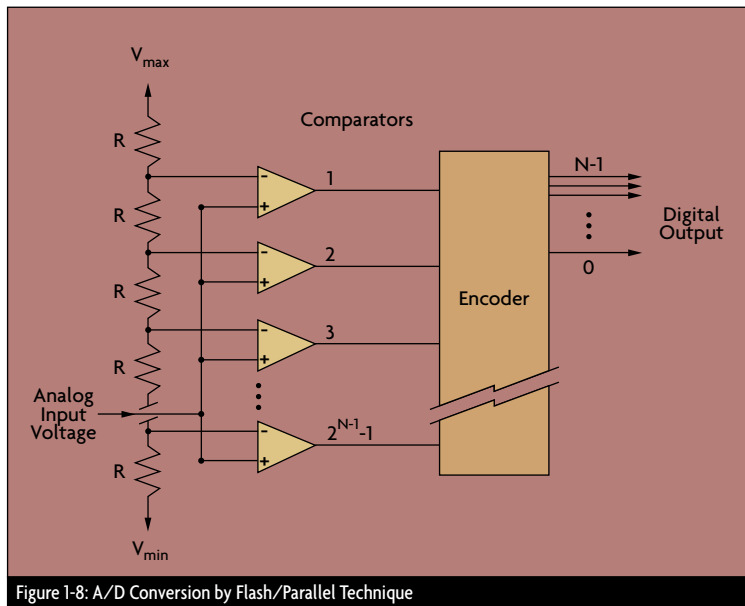


Figure 1-8: A/D Conversion by Flash/Parallel Technique

for. This design uses multiple comparators in parallel to process samples at more than 100 MHz with 8 to 12-bit resolution. Conversion is accomplished by a string of comparators with appropriate references operating in parallel (Figure 1-8).

The downside of this design is the large number of relatively expensive comparators that are required—for example, a 12-bit converter requires 4,095 comparators.

- **Integrating:** This type of A/D converter integrates an unknown input voltage for a specific period of time, then integrates it back down to zero. This time is compared to the amount of time taken to perform a similar integration on a known reference voltage. The relative times required and the known reference voltage then yield the unknown input voltage. Integrating converters with 12 to 18-bit resolution are available, at raw sampling rates of 10-500 kHz.

Because this type of design effectively averages the input voltage over time, it also smoothes out sig-

nal noise. And, if an integration period is chosen that is a multiple of the ac line frequency, excellent common mode noise rejection is achieved. More accurate and more linear than successive approximation converters are a good choice for low-level voltage signals.

- **Ramp/counter:** Similar to successive approximation designs, counting or ramp-type A/D converters use one comparator circuit and a D/A converter (Figure 1-9). This design progressively increments a digital counter and with each new count generates the corresponding analog

voltage and compares it to the unknown input voltage. When agreement is indicated, the counter contains the digital equivalent of the unknown signal.

A variation on the counter method is the ramp method, which substitutes an operational amplifier or other analog ramping circuit for the D/A converter. This technique is somewhat faster.

Multiplexing & Signal Conditioning

As shown in Figure 1-5, A/D converters seldom function on their own but must be considered in a systems context with associated circuitry for signal conditioning, multiplexing, amplification, and other functions. Every application will dictate a unique mix of add-ons that may be implemented in a variety of physical configurations—on a PC I/O board, inside a remote transmitter, or at a local termination panel.

- **Multiplexing:** In many industrial and laboratory applications, multiple analog signals must be converted to digital form. And if speed is not the limiting factor, a single A/D converter often is shared among multiple input channels via a switching mechanism called a multiplexer. This is commonly done because of the relatively high cost of converters. Multiplexers also allow amplification and other signal conditioning circuitry

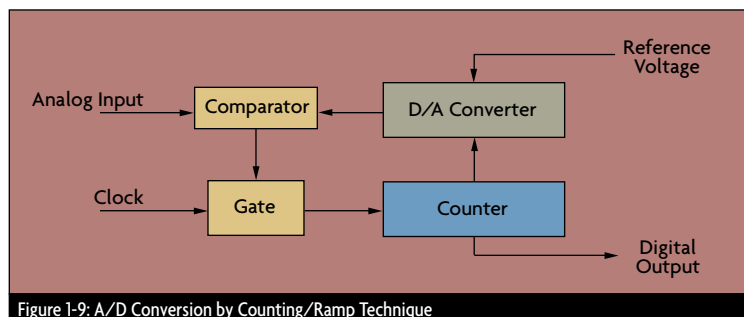


Figure 1-9: A/D Conversion by Counting/Ramp Technique

to be time-shared among multiple channels. Software or auxiliary hardware controls the switch selection.

- **Sample-and-hold:** It is important to acknowledge that a multiplexer

capacitor on each channel tracks the corresponding input signal. Before starting the A/D conversion process, all switches are opened simultaneously, leaving the last instantaneous

er behave more like an 18-bit converter. This function does, however, slow down the sample rate.

From a systems perspective, amplifier performance should be on par with that of the A/D converter itself—gain accuracy should be specified as a low percentage of the total gain. Amplifier noise and offset error also should be low.

- **Other conditioning functions:** Other A/D signal conditioning functions required will vary widely from application to application. Among the options:

- **Current-to-voltage conversion:** A 4-20 mA current signal can be readily converted to a voltage signal using a simple resistor (Figure 1-11). A resistor value of 250 ohms will yield a 1-5 V output.
- **Filtering:** A variety of physical devices and circuits are available to help separate desired signals from specific frequencies of undesirable electrical noise such as ac

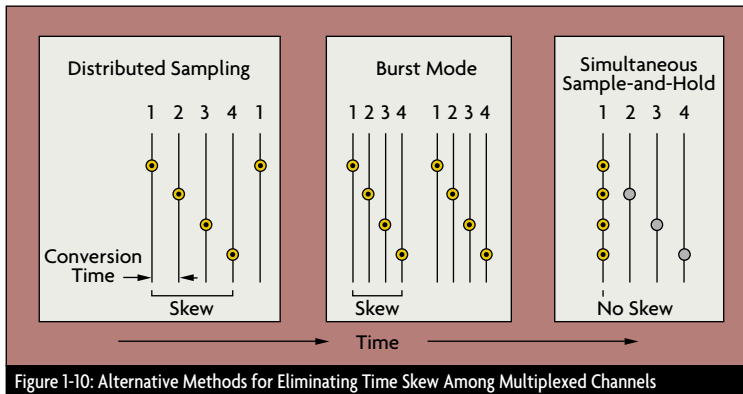


Figure 1-10: Alternative Methods for Eliminating Time Skew Among Multiplexed Channels

does reduce the frequency with which data points are acquired, and that the Nyquist sample-rate criterion still must be observed. During a typical data acquisition process, individual channels are read in turn sequentially. This is called standard, or distributed, sampling. A reading of all channels is called a scan. Because each channel is acquired and converted at a slightly different time, however, a skew in sample time is created between data points (Figure 1-10).

If time synchronization among inputs is important, some data acquisition cards offer “burst” mode operation or simultaneous “sample-and-hold” circuitry. Burst mode, or pseudo-simultaneous sampling, acquires each channel at the maximum rate of the board, then waits a user-specified amount of time before sampling again.

True simultaneous sample-and-hold systems can sample all channels within a few nanoseconds of each other, eliminating phase and time discontinuities for all but the fastest processes. Essentially, a switched

values on the capacitors.

- **Signal scaling:** Because A/D converters work best on signals in the 1-10 V range, low voltage signals may need to be amplified before conversion—either individually or after multiplexing on a shared circuit. Conversely, high voltage signals may need to be attenuated.

Amplifiers also can boost an A/D converter’s resolution of low-level signals. For example, a 12-bit A/D converter with a gain of 4 can digitize a signal with the same resolution as a 14-bit converter with a gain of 1. It’s important to note, however, that fixed-gain amplifiers, which essentially multiply all signals proportionately, increase sensitivity to low voltage signals but do not extend the converter’s dynamic range.

Programmable gain amplifiers (PGAs), on the other hand, can be configured to automatically increase the gain as the signal level drops, effectively increasing the system’s dynamic range. A PGA with three gain levels set three orders of magnitude apart can make a 12-bit convert-

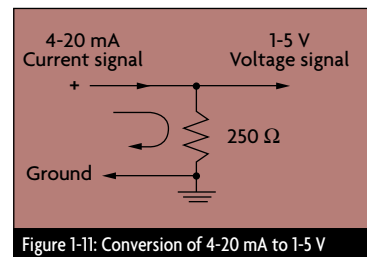


Figure 1-11: Conversion of 4-20 mA to 1-5 V

line pick-up and other electromagnetic/radio frequency interference (EMI/RFI). If the signal of interest is lower in frequency than the noise, a low-pass filter can be used. High-pass and notch-band filters are designed to target low frequency interference and specific frequency bands, respectively.

- **Excitation:** Voltage supplied by the data acquisition card or discrete signal conditioner to certain types of

transducers such as strain gages.

- Isolation: Used to protect personnel and equipment from high voltages. Isolators block circuit overloads while simultaneously passing the signal of interest.

Single-Ended & Differential Inputs

Another important consideration when specifying analog data acquisition hardware is whether to use single-ended or differential inputs (Figure 1-12). In short, single-ended inputs are less expensive but can be problematic if differences in ground potential exist.

In a single-ended configuration, the signal sources and the input to the amplifier are referenced to ground. This is adequate for high level signals when the difference in ground potential is relatively small. A difference in ground potentials, however, will create an error-causing current flow through the ground conductor otherwise known as a ground loop.

Differential inputs, in contrast, connect both the positive and negative inputs of the amplifier to both ends of the actual signal source. Any ground-loop induced voltage appears in both ends and is rejected

as a common-mode noise. The downside of differential connections

under test. Digital-to-analog (D/A) conversion is in many ways the con-

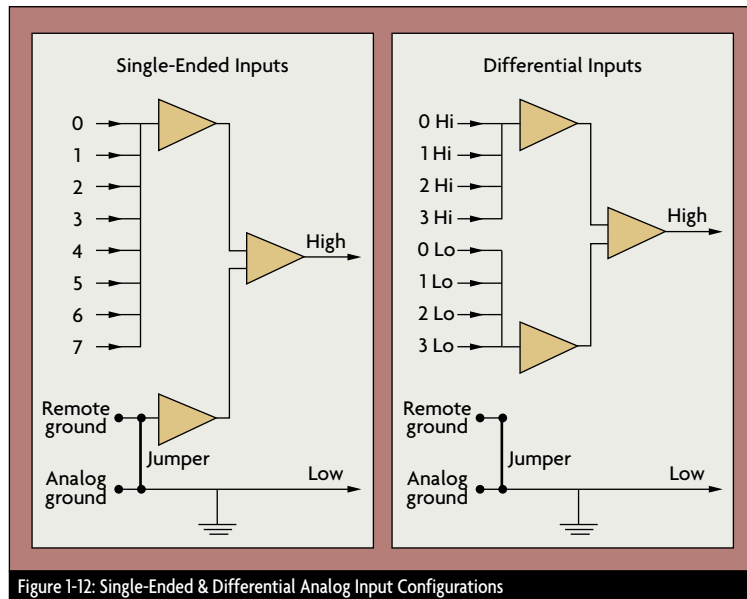


Figure 1-12: Single-Ended & Differential Analog Input Configurations

is that they are essentially twice as expensive as single-ended inputs; an eight-channel analog input board can handle only four differential inputs.

D/A Conversion

Analog outputs commonly are used to operate valves and motors in industrial environments and to generate inputs for electronic devices

verse of A/D conversion, but tends to be generally more straightforward. Similar to analog input configurations, a common D/A converter often is shared among multiplexed output signals. Standard analog output ranges are essentially the same as analog inputs: ± 5 V dc, ± 10 V dc, 0-10 V dc, and 4-20 mA dc.

Essentially, the logic circuitry for

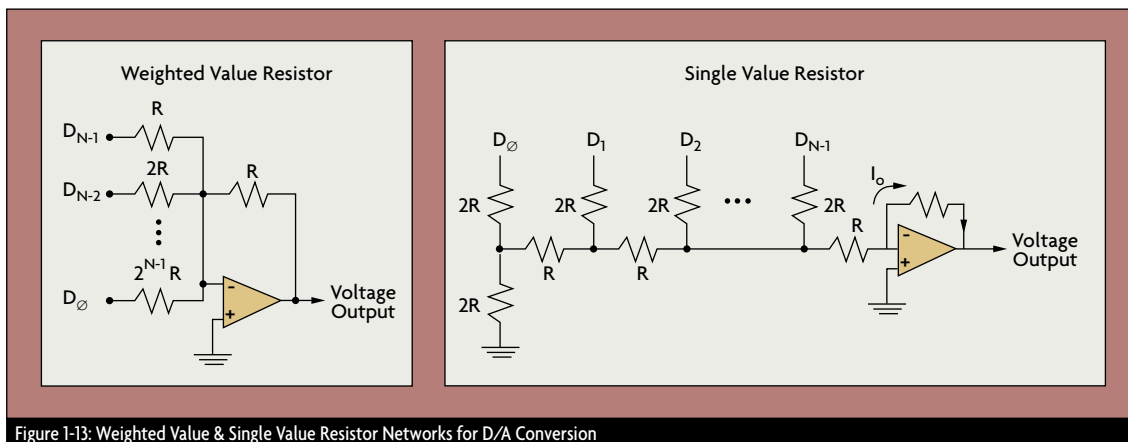


Figure 1-13: Weighted Value & Single Value Resistor Networks for D/A Conversion

an analog voltage output uses a digital word, or series of bits, to drop in (or drop out, depending on whether the bit is 1 or 0) a series of resistors from a circuit driven by a reference voltage. This ladder of resistors can be made of either weighted value resistors or an R-2R network using only two resistor values—one if placed in series (Figure 1-13). While operation of the weighted-value network is more intuitively obvious, the R-2R scheme is more practical. Because only one resistor value need be used, it is easier to match the temperature coefficients of an R-2R ladder than a weighted network, resulting in more accurate outputs. Plus, for high resolution outputs, very high resistor values are needed in the weighted-resistor approach.

Key specifications of an analog output include:

- **Settling time:** Period required for a D/A converter to respond to a full-scale setpoint change.
- **Linearity:** This refers to the device's ability to accurately divide the reference voltage into evenly sized increments.

- **Range:** The reference voltage sets the limit on the output voltage achievable.

Because most unconditioned analog outputs are limited to 5 mA of

current, amplifiers and signal conditioners often are needed to drive a final control element. A low-pass filter may also be used to smooth out the discrete steps in output. **T**

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