Analog to Digital (A/D) Converter

Why do we need Analog to Digital converters?

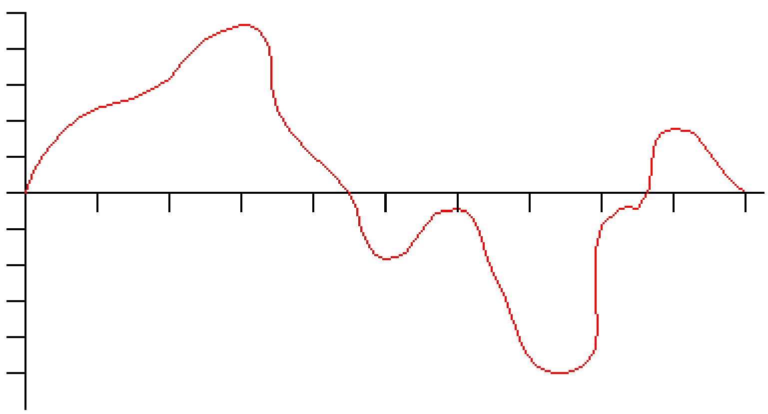
In the real world, most data is characterized by analog signals. In order to manipulate the data using a microprocessor, we need to convert the analog signals to the digital signals, so that the microprocessor will be able to read, understand and manipulate the data.

How does an A/D Converter work?

The main goal of A/D Converter is to digitize the analog signals, which means to record and store the analog signals in NUMBERS. There are two parameters to control in converting the analog signals to the digital signals:

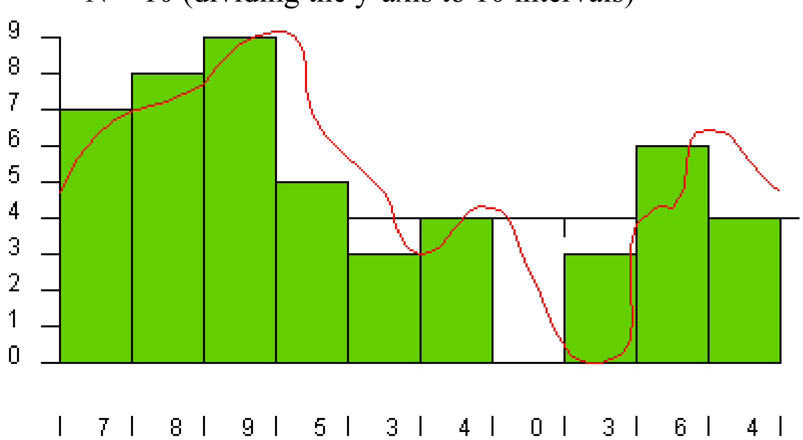
- **Sampling Rate**, *fs* – controls the number of samples taken in a second
- **Sampling Precision**, N – controls the number of different gradations (quantization levels) for the sampling process

Let us consider the following analog signal:

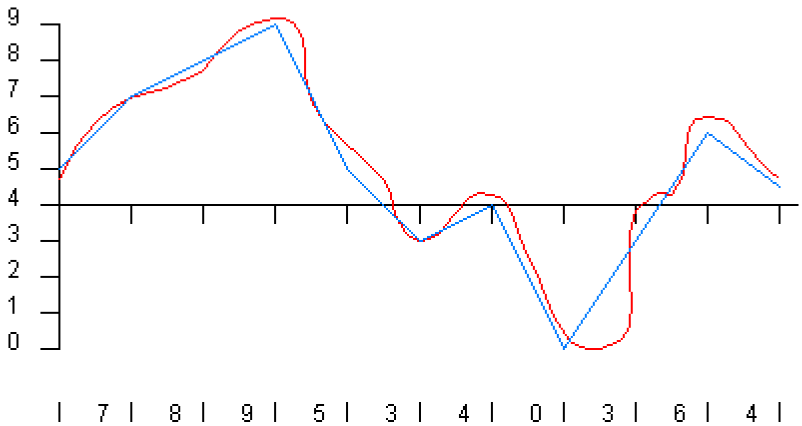


If we assume that:

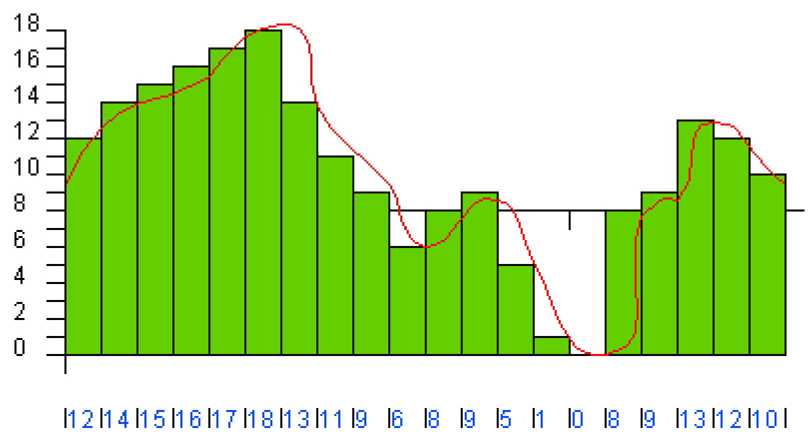
- *fs* = 1000 samples per second
- N = 10 (dividing the y-axis to 10 intervals)



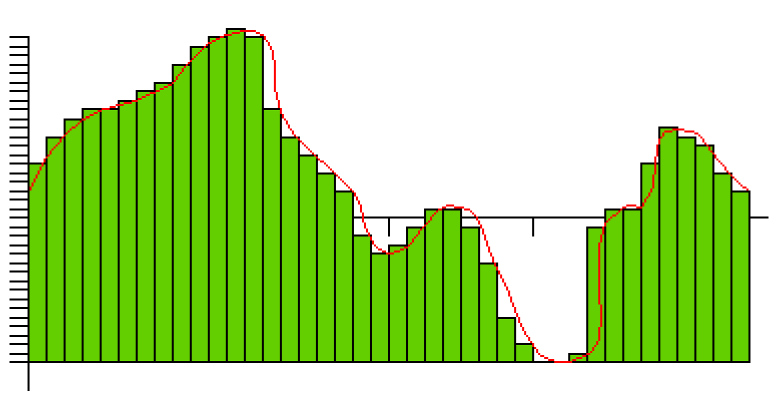
According to the sampling precision, the y-axis is divided into ten intervals (0-9). And according to the sampling frequency, the A/D converter samples the analog signals once per one-thousandth of a second. The A/D Converter then stores the analog signals to the closest number that it can find on the y-axis. The chosen number is indicated on the x-axis of the above figure. According to the digitized data (the number on the x-axis of the above figure), we can plot the following graph showing what the microprocessor is actually reading.



As you can see, we have lost quite a bit of the details of the original wave. This is the sampling error. In order to reduce the sampling error, we must increase the sampling rate, *fs*, and the sampling precision, N. So, if we improve the sampling rate, *fs*, and the sampling precision, N, by a factor of two, we will get the following graph.

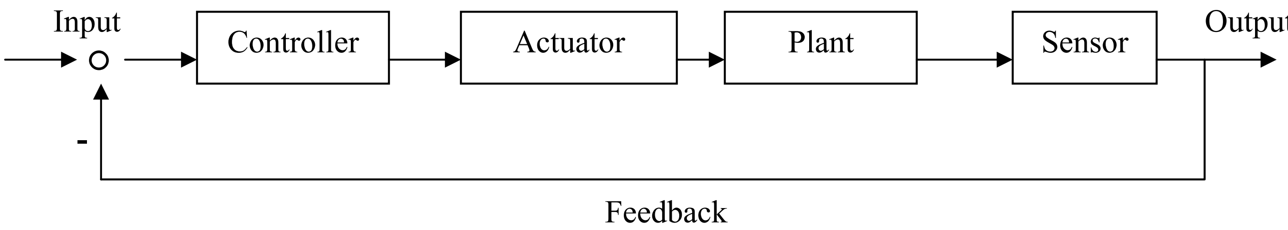


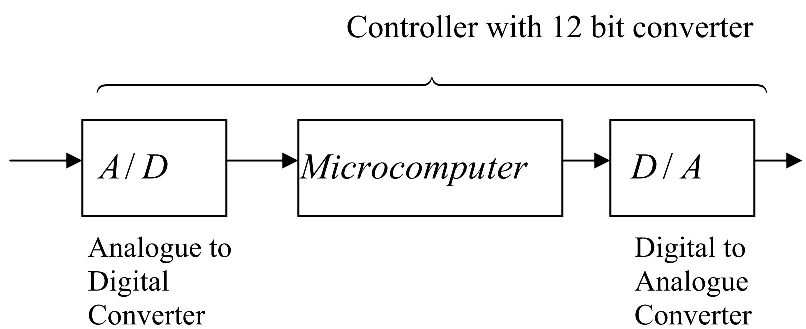
And, if we increase the sampling rate and the sampling precision by a factor of four, we will get the following digitized data.



Therefore, in order to digitize the analog data accurately, we need to sample the analog signal as fast as possible with an A/D that has large number of bits.

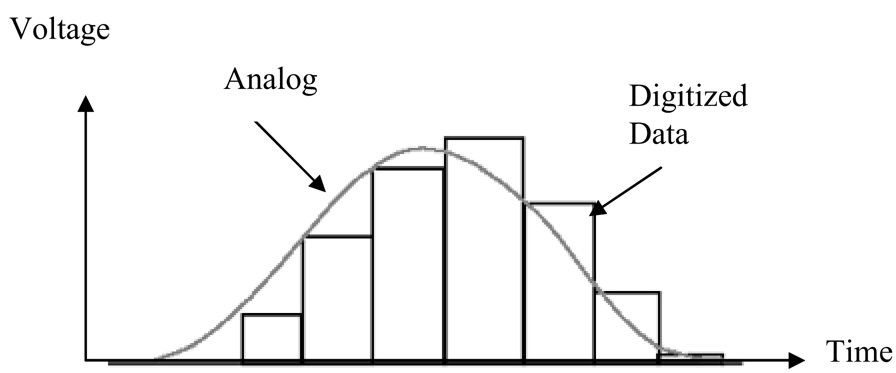
Use of A/D and D/A in Closed Loop Control





$+5V \rightarrow 2^{12} - 1 = 4095$
$4.8828\ V \rightarrow 4000$
$2.4414\ V \rightarrow 2000$
$1.2207\ V \rightarrow 1000$
$0.1221\ V \rightarrow 100$
$0\ V \rightarrow 0$

$4095 \rightarrow +5\ V$
$4000 \rightarrow 4.8828\ V$
$2000 \rightarrow 2.4414\ V$
$1000 \rightarrow 1.2207\ V$
$100 \rightarrow 0.1221\ V$
$0 \rightarrow 0V$



Sampling Theorem:
A signal must be sampled at a rate at least **<u>two times</u>** the maximum frequency component occurring in the signal.

$F_S > 2F\max$

$\downarrow$

SamplingRate

$\Delta T = \dfrac{1}{F_S}$ (*Time between two samples*)

The sampling precision is characterized by the number of the bits in the A/D converter. In other words the number of bits is used to define the quality of an A/D converter (the precision of the A/D converter). The number of bits, n, is related with the number of different gradations, N, by the following equation:

Resolution: $N = 2^n$, where n = number of bits of the A/D converter

$$\left.\begin{array}{l} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ . \\ . \\ . \\ N-1 \end{array}\right\} N$$

Examples:

number of bits (n)	number of different gradations (N)
4	16
8	256
10	1024
12	4096

It can be seen that for a 4-bit a/D converter, the precision of the A/D converter is 1/16 of the full scale of the analog signal. And for a 10-bit A/D converter the precision of the A/D converter is 1/1024 of the full scale of the analog signal. 2407 has a 10-bit converter.

Finally, it is noted that commercial converters are specified for three basic temperature ranges: commercial (0°C to 70°C), industrial (−25°C to 85°C), and military (−55°C to 125°C).

Digital-to-analog (D/A) converters. At the output of the digital controller the digital signal must be converted to an analog signal by the process called digital-to-analog conversion. A digital-to-analog converter is a device that transforms a digital input (binary numbers) to an analog output. Figure 1–24 shows the relationship between the digital input and the analog output for a 3-bit D/A converter. Notice that each digital input (in binary numbers) produces a single continuous-time (analog) output value. The output, in most cases, is the voltage signal.

For the full range of the digital input, there are 2^n corresponding different analog values, including 0. For the digital-to-analog conversion there is a one-to-one correspondence between the digital input and the analog output.

Two methods are commonly used for digital-to-analog conversion: the method using weighted resistors, and the one using the R-$2R$ ladder network. The former is simple in circuit configuration, but its accuracy may not be very good. The latter is a little more complicated in configuration but is more accurate.

Figure 1–25 shows a schematic diagram of a D/A converter using weighted resistors. The input resistors of the operational amplifier have their resistance values weighted in a binary fashion. When the logic circuit receives binary 1 the switch

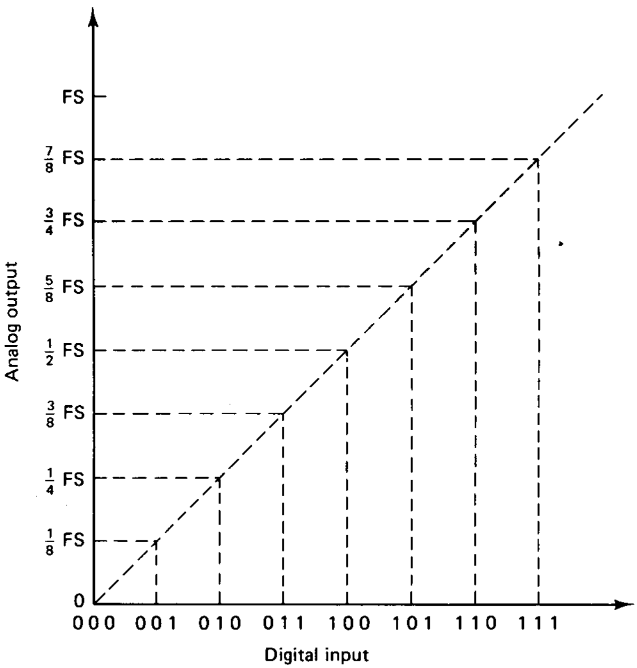


Figure 1–24 Relationship between digital input and analog output for a 3-bit D/A converter.

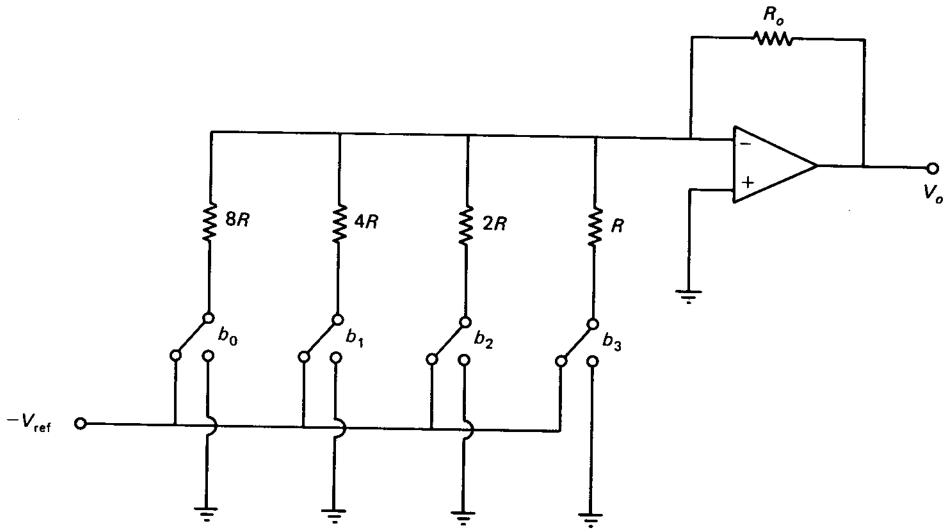


Figure 1–25 Schematic diagram of a D/A converter using weighted resistors.

(actually an electronic gate) connects the resistor to the reference voltage. When the logic circuit receives binary 0, the switch connects the resistor to ground. The digital-to-analog converters used in common practice are of the parallel type: all bits act simultaneously upon application of a digital input (binary numbers).

The D/A converter thus generates the analog output voltage corresponding to the given digital voltage. For the D/A converter shown in Fig. 1–25, if the binary number is $b_3b_2b_1b_0$, where each of the b's can be either a 0 or a 1, then the output is

$$V_o = \frac{R_o}{R}\left(b_3 + \frac{b_2}{2} + \frac{b_1}{4} + \frac{b_0}{8}\right) V_{ref}$$

Notice that as the number of bits is increased, the range of resistor values becomes large and consequently the accuracy becomes poor.

Figure 1–26 shows a schematic diagram of the 4-bit D/A converter using an R-$2R$ ladder circuit. Note that with the exception of the feedback resistor (which is $3R$) all resistors involved are either R or $2R$. This means that a high level of accuracy can be achieved.

Suppose a binary number $b_3b_2b_1b_0$ is given. If $b_3 = 1$ and $b_0 = b_1 = b_2 = 0$, then the circuit shown in Fig. 1–26 can be simplified and an equivalent circuit can be obtained as shown in Fig. 1–27(a). The output voltage is

$$V_o = 3R\frac{i_3}{2} = \frac{1}{2} V_{ref}$$

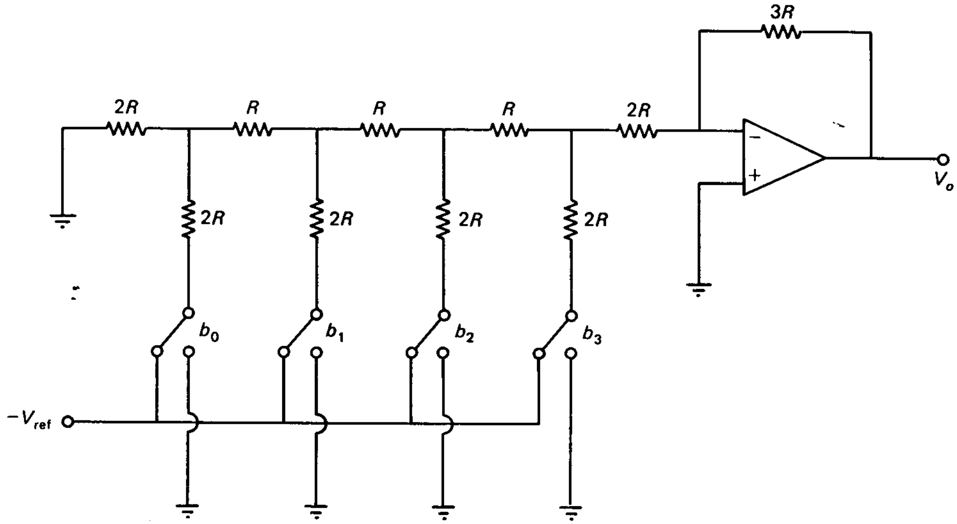


Figure 1–26 4-bit D/A converter using an R-$2R$ ladder circuit.

If $b_2 = 1$ and $b_0 = b_1 = b_3 = 0$, then the equivalent circuit is as shown in Fig. 1–27(b). The output voltage is

$$V_o = 3R\frac{i_2}{4} = \frac{1}{4}V_{\text{ref}}$$

Similarly, if $b_1 = 1$ and $b_0 = b_2 = b_3 = 0$, then the equivalent circuit of Fig. 1–27(c) can be obtained. The output voltage is

$$V_o = 3R\frac{i_1}{8} = \frac{1}{8}V_{\text{ref}}$$

Finally, the circuit shown in Fig. 1–27(d) corresponds to the case where $b_0 = 1$ and $b_1 = b_2 = b_3 = 0$. The output voltage is

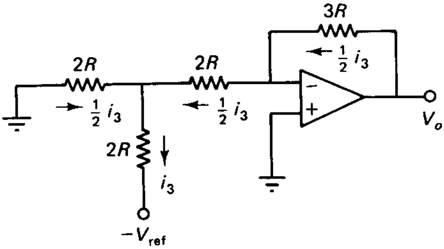
$$V_o = 3R\frac{i_0}{16} = \frac{1}{16}V_{\text{ref}}$$

In this way we find that when the input data is $b_3b_2b_1b_0$ (where the b_i's are either 0 or 1), then the output voltage is

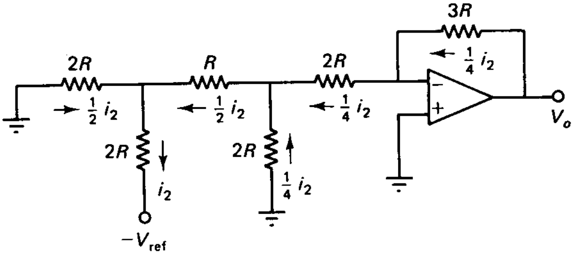
$$\begin{aligned} V_o &= (\tfrac{1}{2}b_3 + \tfrac{1}{4}b_2 + \tfrac{1}{8}b_1 + \tfrac{1}{16}b_0)V_{\text{ref}} \\ &= \tfrac{1}{2}(b_3 + \tfrac{1}{2}b_2 + \tfrac{1}{4}b_1 + \tfrac{1}{8}b_0)V_{\text{ref}} \end{aligned}$$

Figure 1–28 shows a schematic diagram of an n-bit D/A converter using an R-$2R$ ladder circuit. The output voltage in this case can be given by

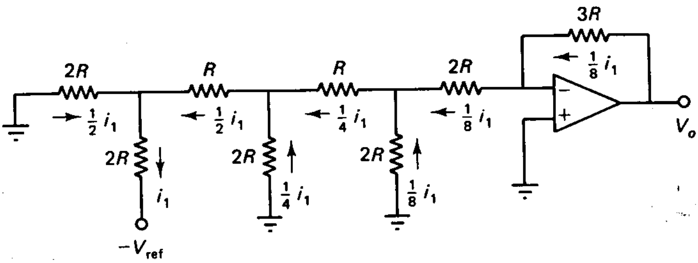
$$V_o = \frac{1}{2}\left(b_{n-1} + \frac{1}{2}b_{n-2} + \cdots + \frac{1}{2^{n-1}}b_0\right)V_{\text{ref}}$$



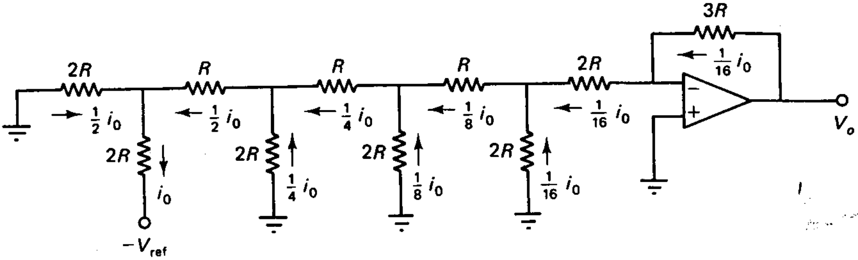
(a)



(b)



(c)



(d)

Figure 1–27 (a) Equivalent circuit of the D/A converter shown in Fig. 1–26 when $b_3 = 1$ and $b_0 = b_1 = b_2 = 0$; (b) equivalent circuit when $b_2 = 1$ and $b_0 = b_1 = b_3 = 0$; (c) equivalent circuit when $b_1 = 1$ and $b_0 = b_2 = b_3 = 0$; (d) equivalent circuit when $b_0 = 1$ and $b_1 = b_2 = b_3 = 0$.

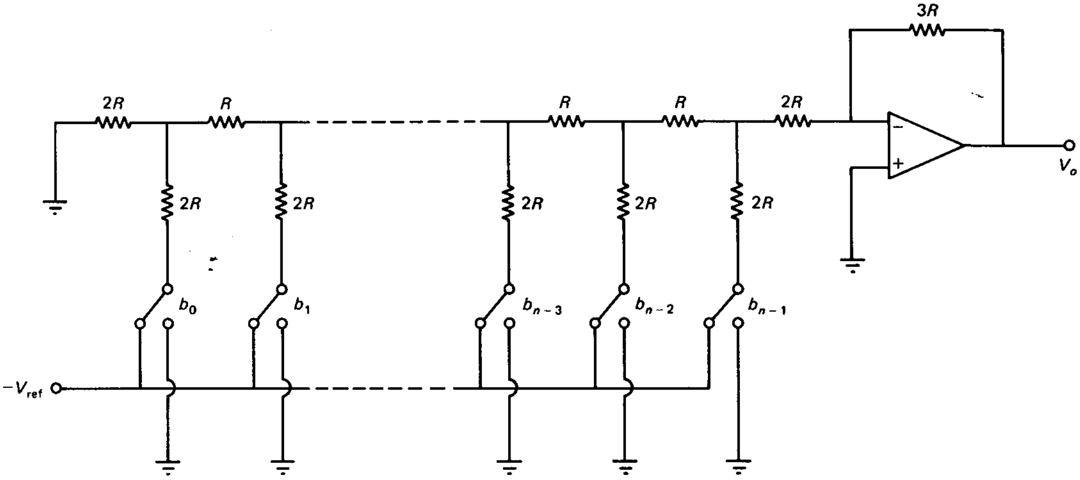
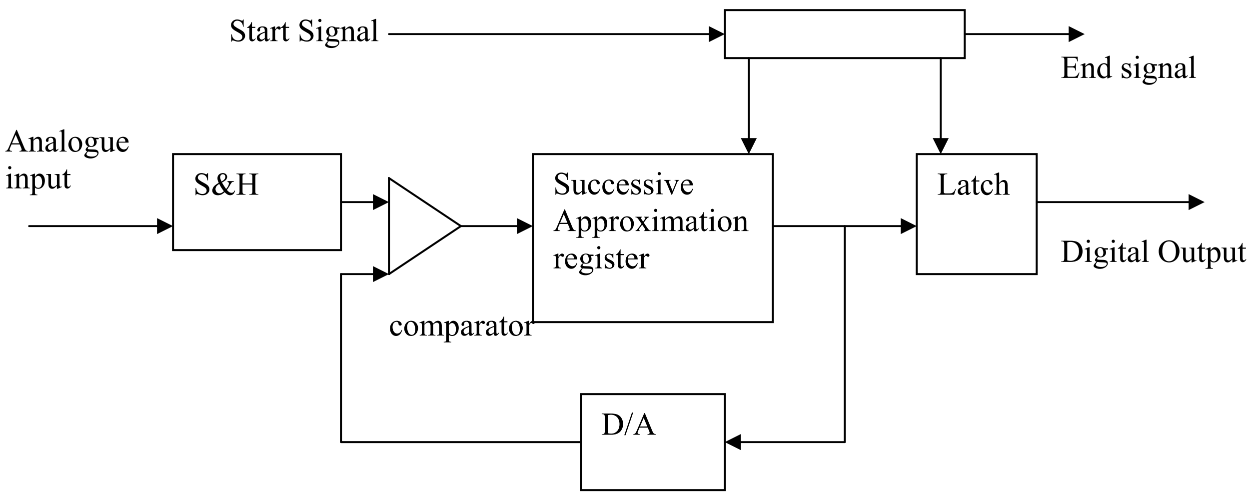
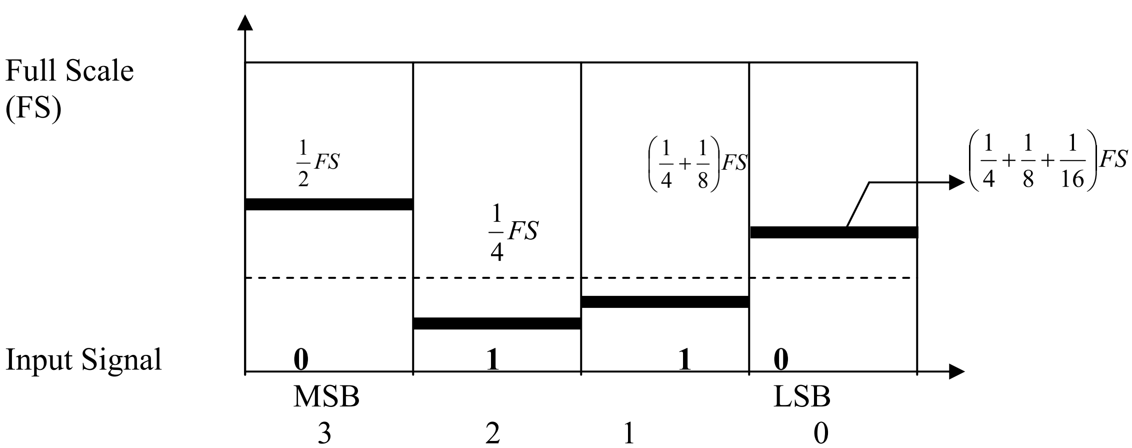


Figure 1–28 n-bit D/A converter using an R-$2R$ ladder circuit.

Analogue to Digital Converter





Result: $[0110]\ or\ 6$