How Digital Devices Understand Real-World Signals

Introduction

In the modern world, we are dependent on digital devices; however, real-world signals (such as voice, audio, video, temperature, and pressure) are usually analog. Digital devices only understand and compute in 1 and 0’s; therefore, the analog-to-digital converters (ADCs) are important components in order to convert the signals to 1 and 0’s. Many devices, including but not limited to cell phones, music recording, air conditioners, and cameras, have ADCs embedded in microcontrollers. ADCs come with many different sizes and shapes depending on applications, and *Figure 1* is one example of many.

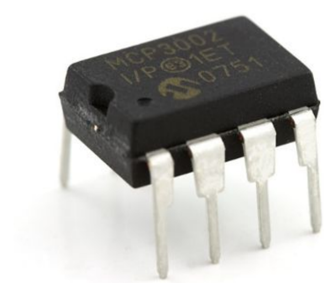


Figure 1: Analog-to-Digital Converter
(Image Source: https://www.sparkfun.com/products/8636)

This process description is geared toward electrical engineering students who understand the importance of converting analog signals to digital signals for industrial purposes, but do not know how the conversion process actually works.

What Are Analog and Digital?

An analog signal is a continuous wave that keeps on changing over a time period. The best example of an analog signal is a human voice, which is a real-world signal. A digital signal is a representation of data as a sequence of discrete values. The fundamental difference between analog and digital signals is that analog signal is represented by the sine waves whereas, the digital signal is represented by square waves.

Figure 2 shows the result of the analog to digital conversion. The goal of this conversion is to take an analog input, which is the sine wave in gray color, and reconstruct it in a digital signal, which is the square wave in red color. The reconstructed signal represents the original signal as a sequence of discrete values.

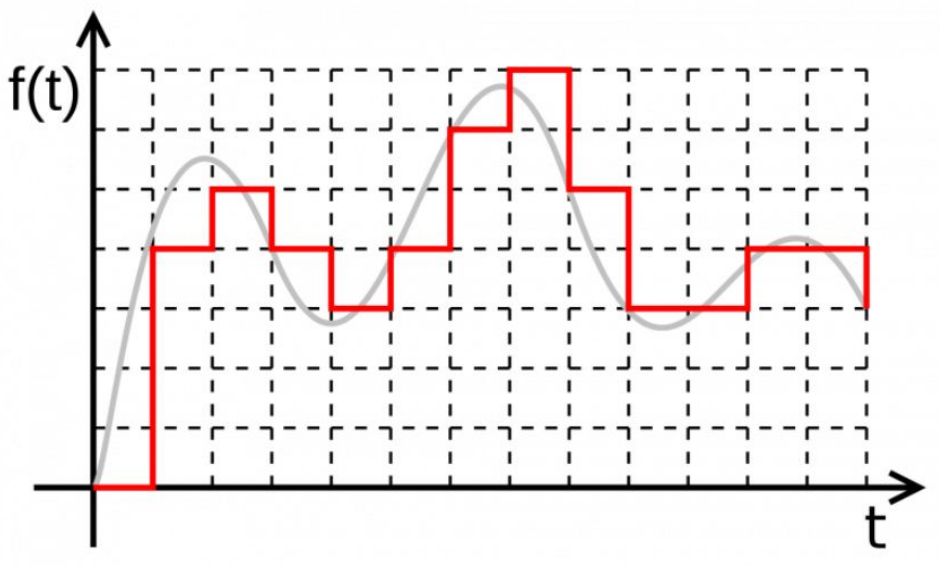


Figure 2: Reconstruction of the Signal From Analog to Digital
(Image Source: https://www.elprocus.com/differences-between-analog-signal-and-digital-signal/)

Overview

The process of analog-to-digital conversion can be broken down into four steps. Once input is put into ADC, it goes through sampling, holding, quantizing, and encoding. Each step is necessary in order to convert the analog input, which is continuous in time and continuous in amplitude, to the digital output, which is in discrete in time and binary (a number system in which only 1 and 0's are used) form as amplitude. An overview of the conversion process is shown in *Figure 3.*

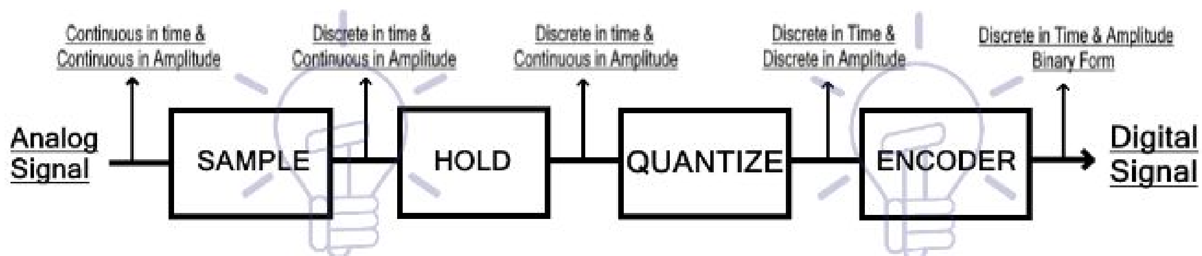
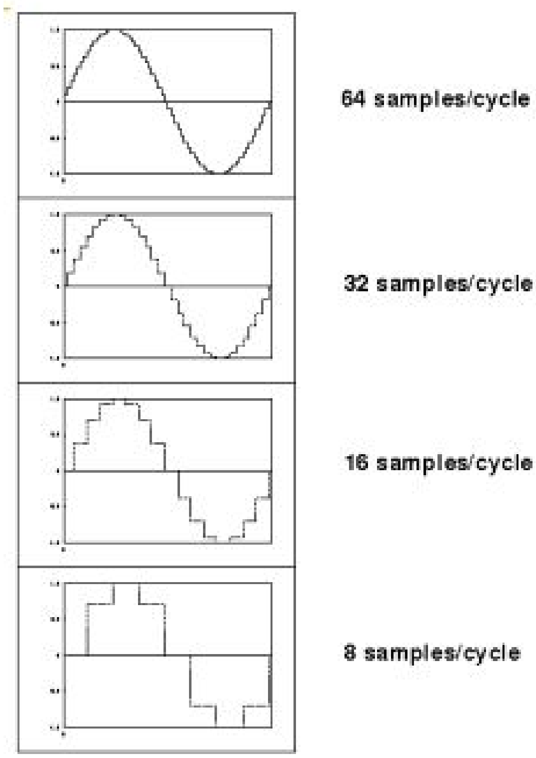


Figure 3: Analog-to-Digital Conversion Process

(Image Source: https://www.electricaltechnology.org/2019/02/analog-to-digital-converter-adc.html)

1. Sample

The analog signal is first sampled at a specific sampling frequency (the rate which determines the number of samples to take per second). For example, The analog signal is measured at uniform time intervals, and this interval is determined by the sampling frequency. The sampling frequency is measured by the number of samples per second. In other words, more data points are taken within a second with a higher sampling frequency.



Higher sampling frequency allows the analog signal to be represented more accurately. *Figure 4* shows how the sampling frequency affects the accuracy of reconstructing the waveform. The original wave is a sine wave. For the same signal, taking 64 samples per cycle represents the signal much more accurately than taking 8 samples per cycle. Although it is better to have a faster sampling frequency, there is a tradeoff. Since more samples need to be taken over the same period, the computation speed of ADCs is much slower for the device with 64 samples per cycle then the device with 8 samples per cycle.

Figure 4: Example of Sampling Frequency (Image Source: https://courses.cs.washington.edu/ courses/cse466/15au/pdfs/lectures/Sampling.pdf)

The sampling frequency is determined based on the need for the application; however, Nyquist Theorem (a principle that needs to be followed when converting signals from analog to digital) must be followed at all cases to avoid aliasing (an effect that the signals to be imperfectly reconstructed due to low sampling frequency). According to the theorem, the sampling frequency must be at least twice as much as the maximum frequency of the input analog signal.

If the sampling frequency is not met with the theorem and is undersampled, as shown in *Figure 5*, the sampled signal causes aliasing. The signal in black color is the original signal, and the blue and orange lines represent the reconstructed signals. However, due to aliasing, none of these reconstructed signals accurately represent the original signal. Also, they look very different from each other even though the reconstruction was based on the same original signal.

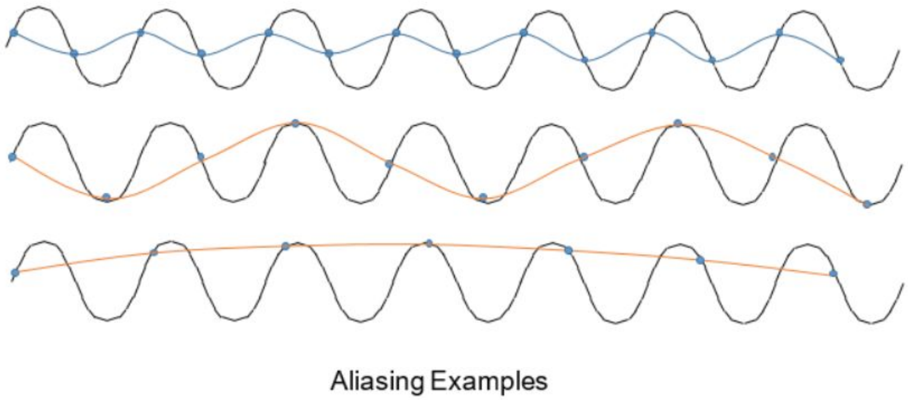


Figure 5: Example of Signal Aliasing
(Image Source: https://www.dataforth.com/anti-aliasing.aspx)

2. Hold

Holding function holds the amplitude of the signal until the next sample is taken. There is no computation or conversion happens in this step. However, it is a necessary step in order to prevent signals from being overwritten. The signal generated by holding is then used in the quantization step.

3. Quantize

Quantization converts the continuous amplitude of the signal into a discrete amplitude. The resolution of the ADC determines the number of discrete steps in the amplitude.

$$Resolution, \triangle V = \frac{V_r}{2^N}$$

Resolution is equal to a reference voltage range divided by the number of states. N represents the number of binary digits (bits), which is the smallest unit of data in a computer, in the digital output. Increasing the number of bits increases the number of states between the voltage range. In other words, having more bits decrease the step size while having more steps; therefore, it increases the accuracy of the ADC.

Figure 6 shows the effect of the resolution for the same analog signal. The original signal is a sine wave, and the figure shows four reconstructed signals with different bit resolution. The effect can be easily seen when comparing 1-bit ADC to 16-bit ADC. 1-bit ADC is only able to represent the signal with two states; however, 16-bit ADC is able to represent the signal with sixteen states. As a result, with 16-bit, the reconstructed signal accurately represents the original sine wave, and it looks like a smooth line even though it actually is a square wave. However, with 1-bit, the reconstructed signal is just a square wave and is far off from the original sine wave.

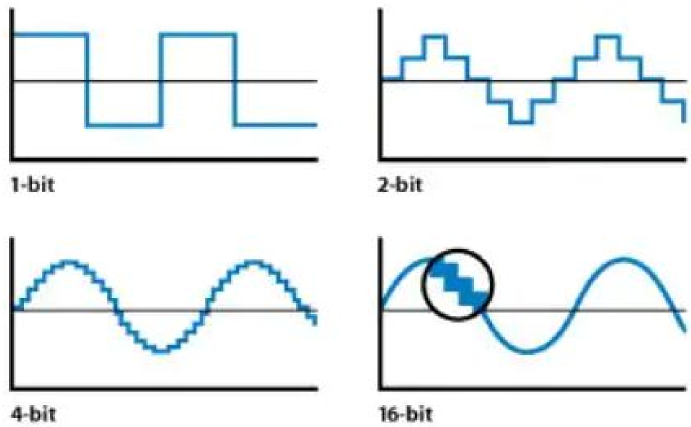


Figure 6: Example of Bit Resolution
(Image Source: https://www.arrow.com/en/research-and-events/articles/engineering-resource-basics-of-analog-to-digital-converters)

4. Encode

An encoder converts the digital signal into a binary form (a number system in which only 1 and 0's are used). The reason for encoding is because digital devices only work in binary form. Digital devices only understand 1 and 0's; therefore, analog input signals need to be converted to a binary form. Once the signal is converted to discrete-time and discrete-amplitude, the amplitude is converted to 1 and 0's. After quantization, each amplitude level is represented by binary form.

Figure 7 is an example of an analog signal which amplitude ranges from 0.5 to 7.5. 3-bit resolution represents the signal with 8 steps. For example, any amplitude value measured between 0.5 to 1.5 is quantized to 1, and encoder outputs as a binary form of 1, which is 001. Any voltage amplitude measured between 1.5 to 2.5 is quantized to 2, and encoder outputs as a binary form of 2, which is 010, and so on.

Analog signal			Digital o/p
7.5	7 →	7Δ=7V →	111
6.5	6 →	6Δ=6V →	110
5.5	5 →	5Δ=5V →	101
4.5	4 →	4Δ=4V →	100
3.5	3 →	3Δ=3V →	011
2.5	2 →	2Δ=2V →	010
1.5	1 →	1Δ=1V →	001
0.5	0 →	0Δ=0V →	000

Figure 7: Example of Binary Form Representation
(Image Source: https://www.electrical4u.com/analog-to-digital-converter/)

Encoding is the last step of analog to digital conversion process. Analog input signals are converted to digital signals, and the signals can be used for digital devices.

Conclusion

Digital devices only understand binary form, which is 1 and 0's; however, real-world signals are analog signals. Since digital devices are used everywhere in the modern world, analog-to-digital conversion is important to convert real-world signals so that those devices can understand the signals. After the analog signals going through the analog-to-digital conversion process, the signals are converted to binary outputs which now can be used for digital devices. This process is done by sampling, holding, quantizing, and encoding the input signals in the order. Cell phones, music recording, air conditioners, and cameras are just a few examples of the devices which use ADCs.