

# **VI. Data Acquisition**

# 1. Analog-to-Digital Conversion

Definition: quantization is the process by which a sampled amplitude value is assigned one of a limited number of fixed values.

Quantization is accomplished for all channels before the next sample is taken (commonly 10  $\mu$ sec per channel).

Definition: coding is the process by which a quantized value is converted to binary notation.

The quantized value is coded into binary form. Typically, each binary digit is assigned an output line. At read-out time, these lines carry a 0 or 1.

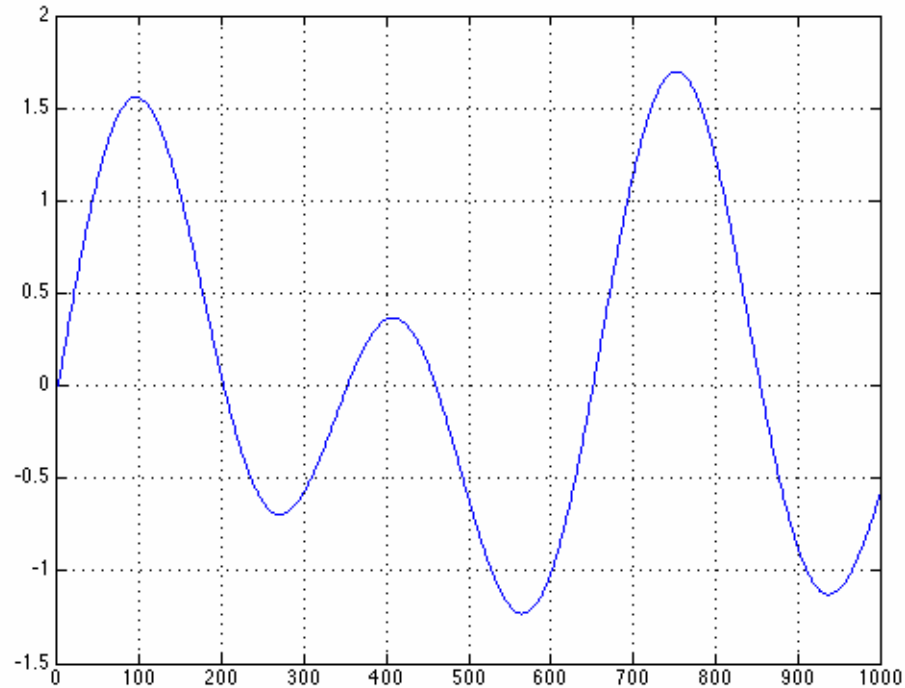
Definition: the sampling interval is the difference in time between successive samples.

Definition: the quantization step size is the smallest possible difference in amplitude between samples.

The resulting digital data is thus both temporally discrete and amplitude discrete.

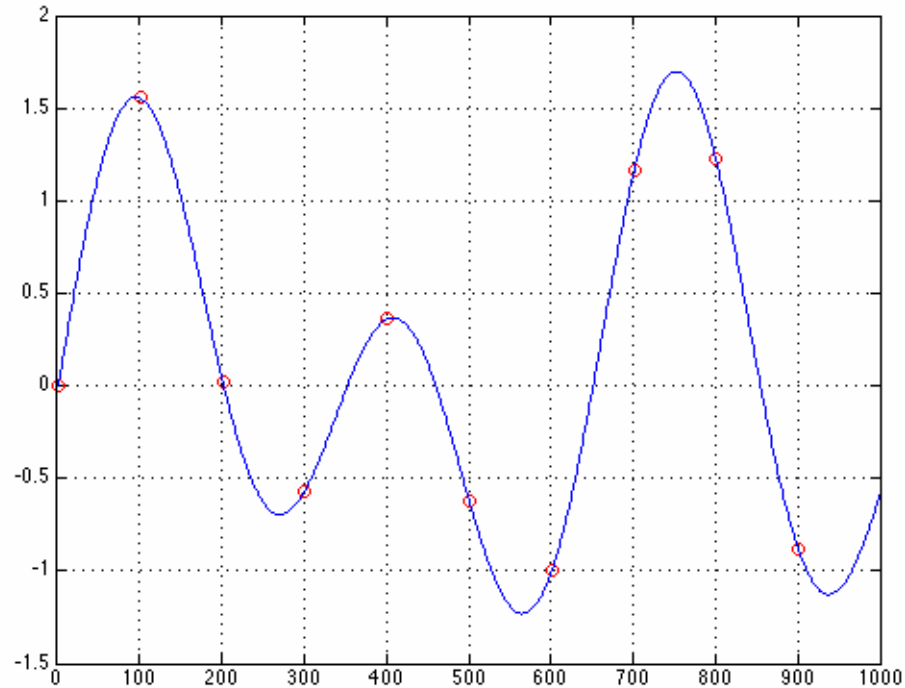
# 1. Analog-to-Digital Conversion

Simulation of Digitization



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The reason there is a fixed quantization step size is that amplitude is represented as a binary number within the A-D converter. The number of bits assigned to each amplitude value determines the quantization step size.

The total number of levels that the quantized values can take is usually an integer power of 2. The degree of precision of an ADC is referred to in terms of the number of bits assigned to each amplitude value. This is the same number of bits in the output word of the converter.

Ex. If each amplitude is assigned 12 bits, then there are  $2^{12}$  (4096) possible quantized values. 011001010111

Definition: dynamic range is the full-scale amplitude extent of allowable input to the ADC. (Dynamic range may also be defined as the amplitude extent of the pre-amplified input signal.)

Any amplitudes outside the dynamic range will be recorded as one of the extreme values. When this happens, the result is known as clipping or saturation.

# 1. Analog-to-Digital Conversion

The quantization step size depends on the dynamic range. When determined in terms of the pre-amplified input signal, it depends on the gain (output/input) of the amplifier, since the gain determines the recorded signal values.

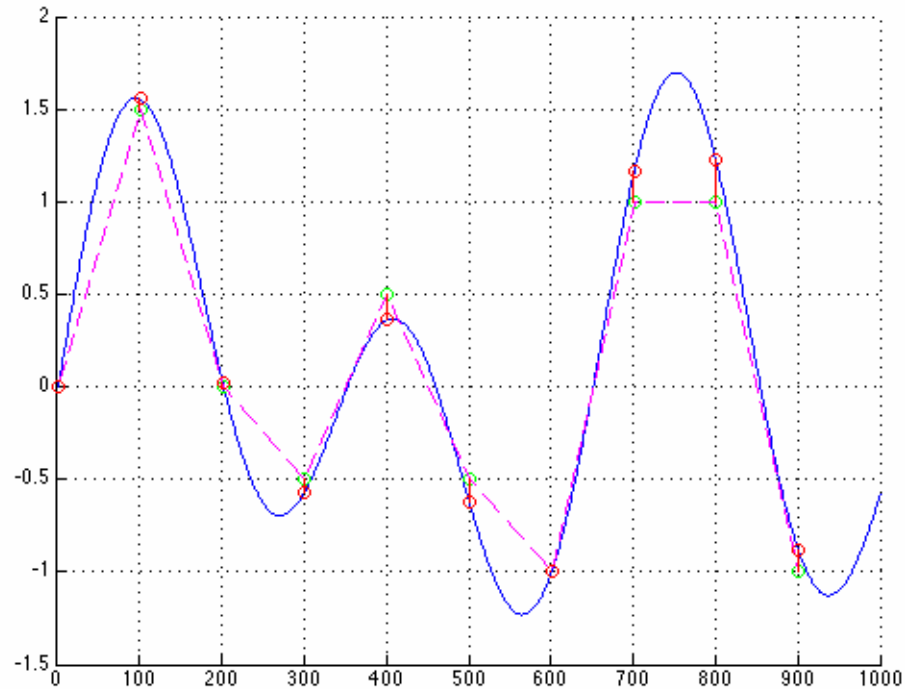
Problem: If the dynamic range of the ADC is +/- 5 V, the amplifier gain is 10K, and the ADC precision is 10 bits, what is the quantization step size with respect to the unamplified data in  $\mu\text{V}$ ?

\*\*\*The dynamic range is 10 V. This range is equivalent to  $10\text{V} / 10\text{K} = 1000 \mu\text{V}$  prior to amplification. 1024 quantization levels are available. There are 1024 levels from -511 to 512.  $1000 \mu\text{V} / 1023 \text{ steps} = 0.978 \mu\text{V}/\text{step}$ .\*\*\*

**NB:** There are 1024 levels, but only 1023 steps!

# 2. Quantization Noise

Definition: quantization noise is the discrepancy between the quantized and true value of the sampled data.



# 2. Quantization Noise

In some cases, the quantization noise is highly correlated.

Example: If the incoming data consists of a repetitive wave exactly synchronized to some multiple of the sampling interval, then the value of the waveform will be the same at each sample and so will the value of the quantization error.

In some cases, it behaves like a random variable.

Example: If the incoming data has a random component, then the quantization noise takes on the characteristics of random noise.

Let us first define the expectation operation. Let  $X$  be a random variable, and let  $\Psi(X)$  represent any quantity derived from it. The expectation of  $\Psi$  is defined as:

$$E[\Psi(X)] \equiv \int_{-\infty}^{\infty} \Psi(X) p(X) dX$$

where  $p(X)$  is the probability density function of  $X$ . (dice example)

# 2. Quantization Noise

In the case where the quantization noise ( $n$ ) is random, the following holds:

(1)  $n$  is uncorrelated with that of its sequential neighbors.

$$E[n(i) * n(i + p)] = 0 \text{ for } p \neq 0$$

(2) the value of  $n$  is uniformly distributed over the interval  $-q/2$  to  $q/2$ , i.e. it is equally likely that the error falls anywhere in this range.

$$p(n) = \begin{cases} \frac{1}{q} & \text{for } -q/2 \leq n < q/2 \\ 0 & \text{otherwise} \end{cases}$$

The mean of the quantization noise is given by:

$$\mu_n = E[n] = \int_{-\infty}^{\infty} n * p(n) dn = \int_{-q/2}^{q/2} \frac{n}{q} dn = \frac{n^2}{2q} \Big|_{-q/2}^{q/2} = \frac{q}{8} - \frac{q}{8} = 0$$

## 2. Quantization Noise

Its variance is given by:

$$\begin{aligned}\sigma_n^2 &= E[(n - \mu_n)^2] = \int_{-\infty}^{\infty} (n - \mu_n)^2 p(n) dn = \int_{-q/2}^{q/2} \frac{n^2}{q} dn \\ &= \frac{n^3}{3q} \Big|_{-q/2}^{q/2} = \frac{q^3}{24q} + \frac{q^3}{24q} = \frac{q^2}{12}\end{aligned}$$

What use can we make of knowing this? The noise variance is a reflection of how well small amplitude fluctuations can be detected. In other words, signals (i.e. variations that we want to detect) must be larger than the quantization noise level, as measured by its variance, in order to be detectable. We can see how this noise variance depends on the dynamic range (R) and the number of digits (d) assigned to each quantized amplitude value.

We already saw that the quantization step size may be expressed as:

$$q = \frac{R}{2^d - 1}$$

where d is the number of digits (bits) assigned to each amplitude value.

## 2. Quantization Noise

Substitution for  $q$  into the equation for variance gives:

$$\sigma_n^2 = \frac{\left[ \frac{R}{2^d - 1} \right]^2}{12} \approx \frac{R^2 2^{-2d}}{12}$$

Note that the noise variance decreases exponentially with increasing  $d$ .

Thus, the noise level could be made arbitrarily small if  $d$  could be made arbitrarily large.

# 3. The Trade-off Between Saturation and Resolution

Quantization noise tends to make small fluctuations less detectable. This can be a problem since there are often cases where one is interested in these fluctuations. As discussed before, low-amplitude waves tend to be at high-frequencies, such as the gamma range. This range has considerable interest for cognitive function.

To increase the resolution of small amplitude fluctuations, the amplification gain can be increased.

However, amplification applies equally to all frequencies. If the input data also contain large-amplitude, low-frequency components (e.g. baseline drift), then increasing the gain may cause appreciable saturation.

Thus, we see that there is a trade-off between achieving adequate resolution of low-amplitude fluctuations by increasing amplification, and avoiding saturation of high-amplitude components by decreasing amplification. That is:

Lowering the amplifier gain decreases the resolution of small components. Small peaks may be reduced to only a few increments of the quantization step size, making the quantization noise an important factor. But increasing the amplifier gain may cause saturation.

# 3. The Trade-off Between Saturation and Resolution

The problem can be reduced by using an ADC with the greatest precision (i.e. most bits) possible. Apart from that, the probability of saturation can be reduced, and smaller peaks better made to fill the dynamic range, by filtering out the low-frequency component at the amplification stage. It is also possible to record low-frequency and high-frequency activity without saturation by splitting the unfiltered input data into two amplifiers, one with a low-pass filter to record low-frequency components with lower gain, and the other with a high-pass filter to record high-frequency components with higher gain. A faster sampling rate would be needed for the high-frequency channel than for the low-frequency one. This procedure is commonly used with intra-cortical microelectrode recordings, where it is desirable to record both field potential and multi-unit spiking activity from the same electrode.

Another sophisticated solution to the resolution/saturation problem is to dynamically adjust the input range of the ADC as needed to avoid saturation. This is implemented in one ADC by simultaneous sampling with 3 different input ranges. For any point, the ADC selects the one with greatest resolution that isn't saturated.

# 4. Multiplexing

Definition: multiplexing is the process whereby several data sources have their information transmitted to the data processor over the same line.

(1) Most ADCs have multiplexing capability so that 1 converter is used to convert multiple input channels.

Ex. when there are several scalp electrodes being monitored at the same time, then the converted data may be multiplexed.

(2) There is a minimum conversion time for each sample of data. This conversion time must be multiplied by the number of channels being sampled to get the total sampling time. This sampling time is also known as slew time since there is a delay between the sample times of the different channels.

Ex. if the conversion time is 10  $\mu\text{sec}/\text{sample}$  and there are 10 channels, then the slew time is 100  $\mu\text{sec}$ .

# 4. Multiplexing

(3) The slew time limits the sampling rate, since all the channels must be sampled for one time step before sampling can begin on the next time step. This means that the ADC has a maximum number of sample points that can be collected per second. If more channels are sampled, the maximum sampling rate per channels is reduced.

Ex. if the ADC has a maximum capacity of 100K samples/sec, then a single channel can be sampled at 100K/sec. If we want to sample 100 channels, then the maximum rate per channel is 1K/sec.