7.0 Quantization and Pulse Code Modulation

If eight bits are allowed for the PCM sample, this gives a total of 256 possible values. PCM assigns these 256 possible values as 127 positive and 127 negative encoding levels, plus the zero-amplitude level. (PCM assigns two samples to the zero level.) These levels are divided up into eight bands called **chords**. Within each chord is sixteen **steps**. Figure 23 shows the chord/step structure for a linear encoding scheme.

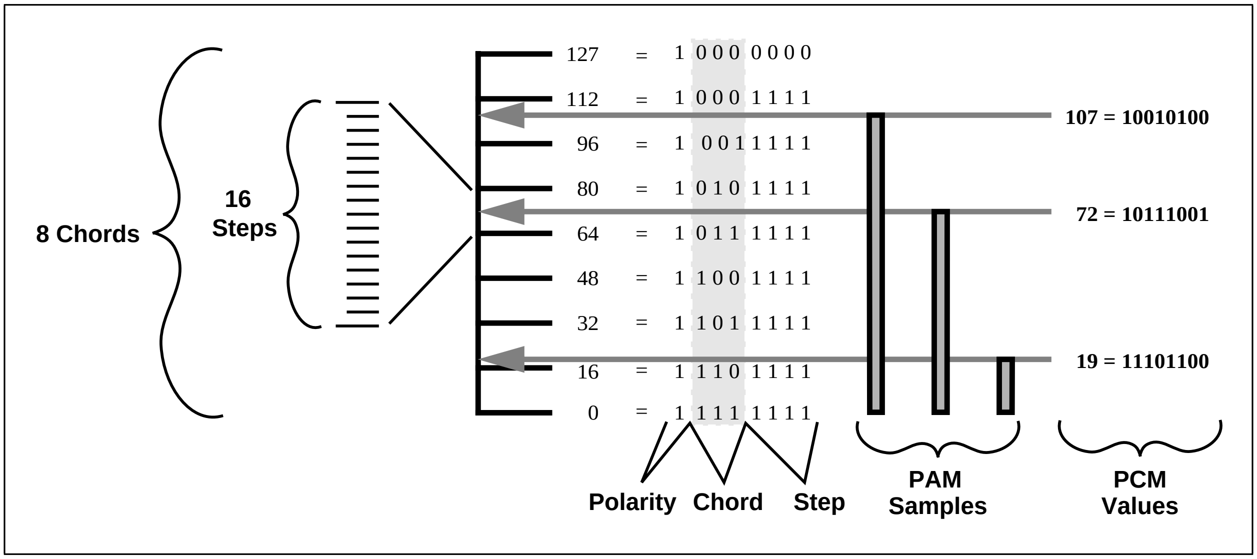

Figure 23: PCM Quantization levels - Chords and Steps

Three examples of PAM samples are shown in Figure 23. Each PAM sample's peak falls within a specific chord and step, giving it a numerical value. This value translates into a binary code which becomes the corresponding PCM value. Figure 23 only shows the positive-value PCM values, for simplicity.

Figure 24 shows the conversion function for a linear quantization process. As a voice signal sample increases in amplitude the quantization levels increase uniformly. The 127 quantization levels are spread evenly over the voice signal's dynamic range. This gives loud voice signals the same degree of resolution (same step size) as soft voice signals. Encoding an analog signal in this manner, while conceptually simplistic, does not give optimized fidelity in the reconstruction of human voice.

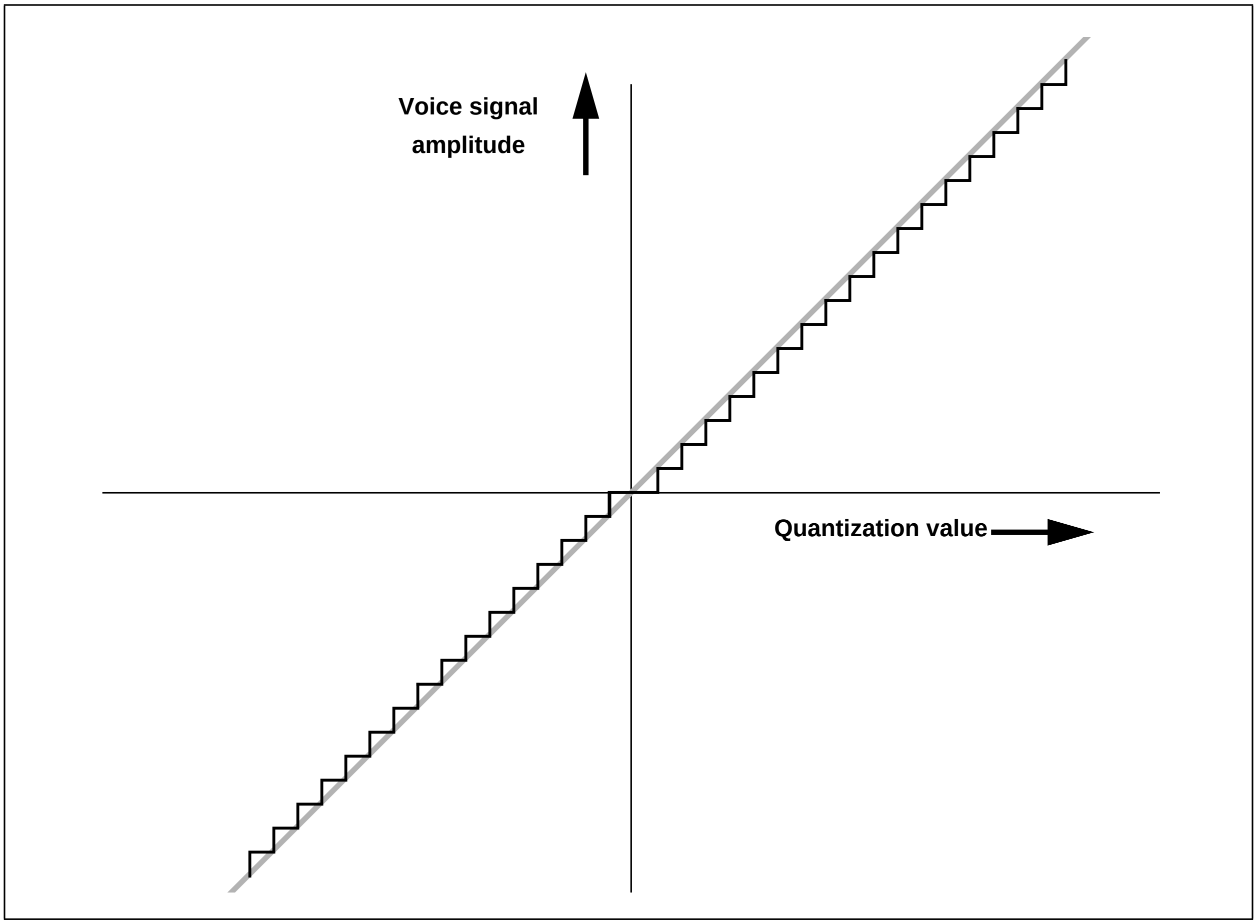

Figure 24: Linear Quantization, Signal Amplitude versus Quantization Value

Notice this transfer function gives two values for a zero-amplitude signal. In PCM, there is a “positive zero” and a “negative zero”.

7.1 Companding

Dividing the amplitude of the voice signal up into equal positive and negative steps is not an efficient way to encode voice into PCM. Figure 23 shows PCM chords and steps as uniform increments (such as would be created by the transfer function depicted in Figure 24). This does not take advantage of a natural property of human voice: voices create low-amplitude signals most of the time (people seldom shout on the telephone). That is, most of the energy in human voice is concentrated in the lower end of voice’s dynamic range.

To create the highest-fidelity voice reproduction from PCM, the quantization process must take into account this fact that most voice signals are typically of lower amplitude. To do this the vocoder adjusts the chords and steps so that most of them are in the low-amplitude end of the total encoding range. In this scheme, all step sizes are not equal. Step sizes are smaller for lower-amplitude signals.

Quantization levels distributed according to a logarithmic, instead of linear, function gives finer resolution, or smaller quantization steps, at lower signal amplitudes. Therefore, higher-fidelity reproduction of voice is achieved. Figure 25 shows a conversion function for a logarithmic quantization process.

A vocoder that places most of the quantization steps at lower amplitudes by using a non-linear function, such as a logarithm, is said to compress voice upon encoding, then expand the PCM samples to re-create an analog voice signal. Such a vocoder is hence called a **compander** (from **com**press and ex**pand**).

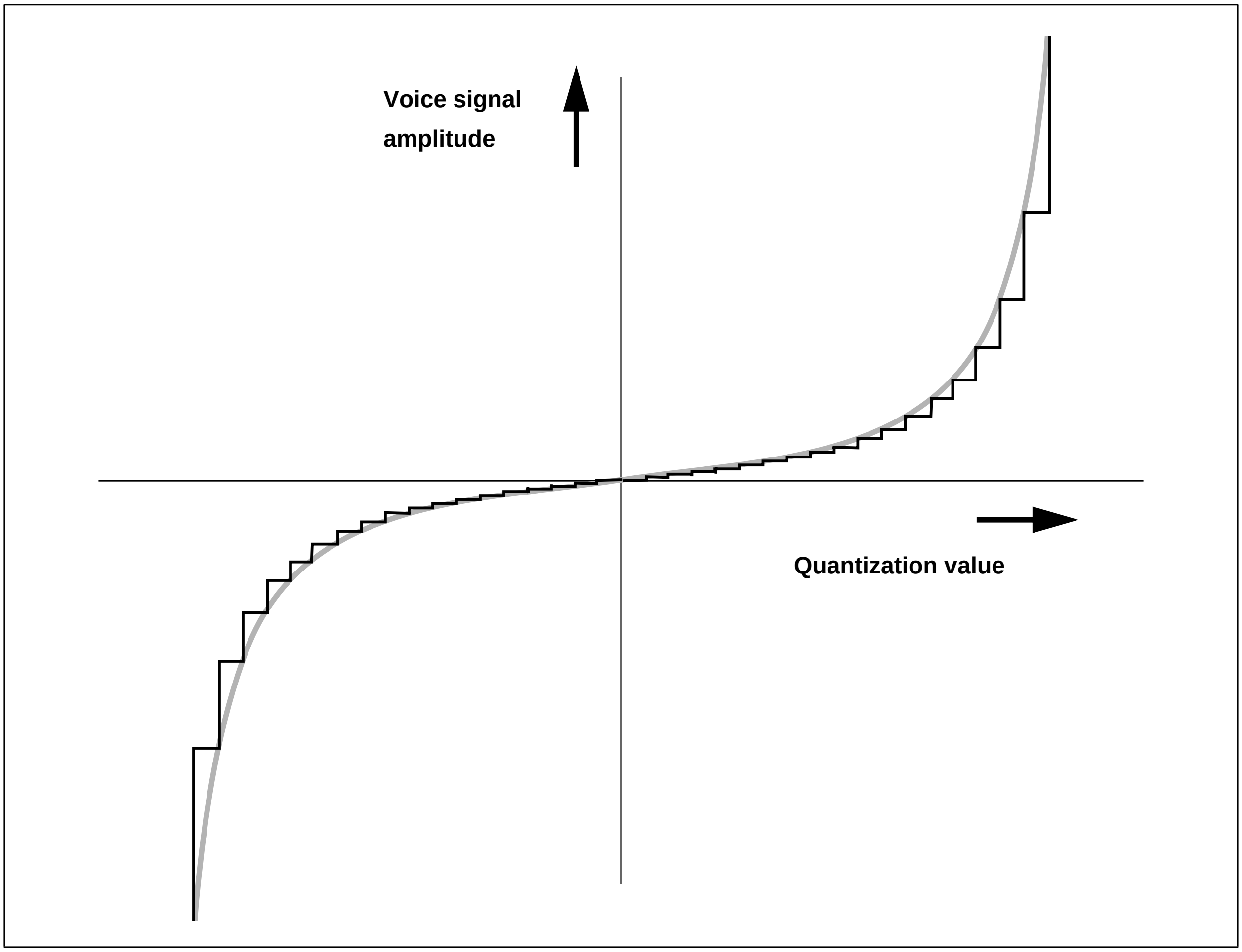

Figure 25: Logarithmic Quantization, Signal Amplitude versus Quantization Value

In reality, voice quantization does not exactly follow the logarithmic curve step for step, as Figure 25 appears to indicate. PCM in North America uses a logarithmic function called **μ-law**. The encoding function only approximates a logarithmic curve, as steps within a chord are all the same size, and therefore linear. The steps change in size only from chord to chord. The chords form linear segments that approximate the μ-law logarithmic curve. The chords form a piece-wise linear approximation of the logarithmic curve.

7.2 Quantization Error

Figure 26 shows three PAM samples that have their amplitudes measured and given PCM values. If a PAM sample's level lies between two steps, it is assigned the value of the highest step it crosses. A PAM sample that just reaches this step would be given the same quantization value. Therefore, all PAM samples are treated as if they fall exactly on a step level.

PAM samples with amplitudes that are not close to each other (e.g., B & C in Figure 26) can be given the same quantization value. Even though the PAM samples represent different amplitudes of the original signal, they receive the same PCM value. This causes an impreciseness in the voice encoding process called **quantization error.**

Figure 26 shows how the quantization process can alter a voice signal. Samples A and B are closest in amplitude, with C being much lower. However, due to how the samples fall into the quantization levels, the sample steps created from the PCM words have B and C at the same amplitude. Obviously, the reconstructed waveform will be different from the original waveform.

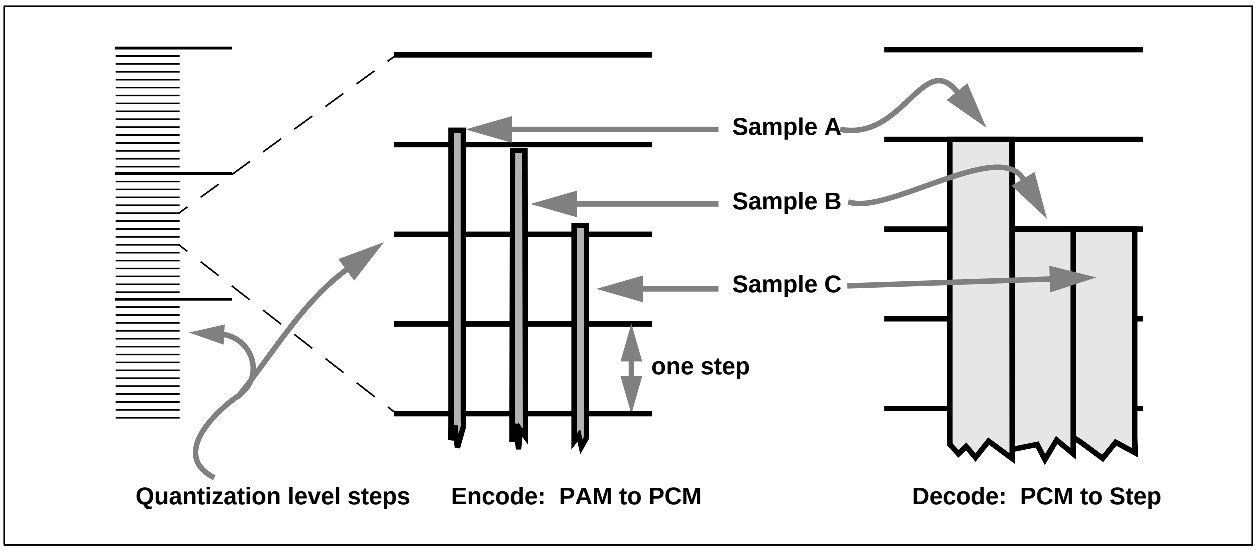

Figure 26: Quantization Error: Recovered Step levels do not match PAM levels

7.2.1 Fidelity: Maintaining a high Signal-to-Noise ratio

Quantization error is another reason for using compressed encoding for digitizing a voice signal. Compressed encoding allows a higher signal-to-quantization-noise ratio (SN_QR) than linear encoding. This ratio defined as

$$SN_QR = 20\log\left\langle\frac{S}{N_Q}\right\rangle$$

where S is the voice signal level and N_Q is noise due to the quantization error. Clearly, keeping the quantization error small is key to keeping a high SN_QR. As signal amplitude gets smaller, N_Q must get smaller to keep SN_QR from dropping. Compression accomplishes this by forcing quantization error magnitude to decrease with lower amplitudes.

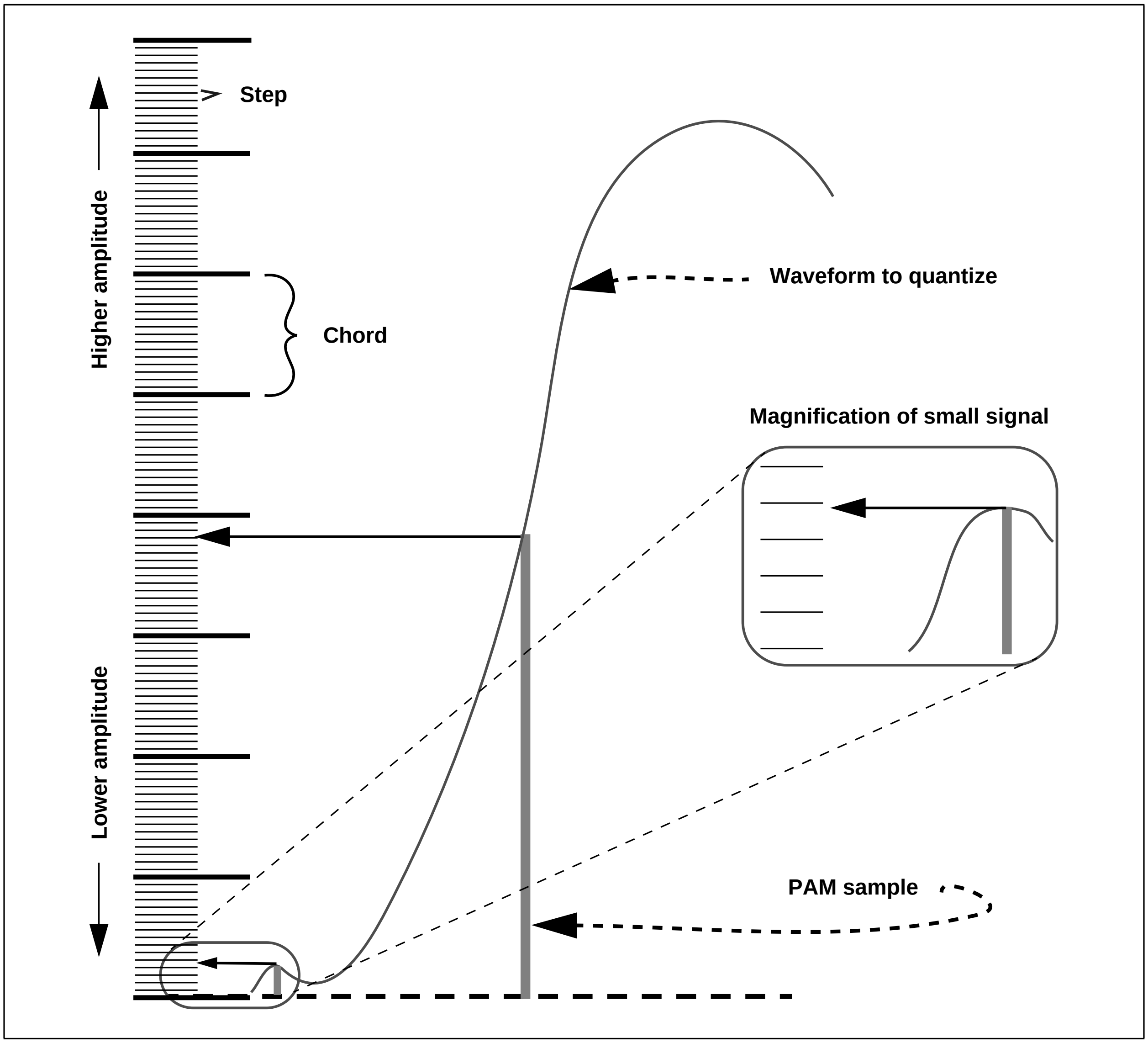

Figure 27: Linear Quantization, another View

Without increasing the overall number of quantization samples, it is desirable to increase the SN_QR for small-amplitude signals. This is what logarithmic quantization accomplishes.

Figure 27 gives another view (as opposed to Figure 24) of the scale for a linear quantizer. The quantization levels are shown to the left for the positive range of a voice waveform. This is only the positive half of the quantization scale. There is a mirror image scale for the negative half of the voice signal (not shown here for simplicity). The magnification of a small-amplitude portion of the voice signal shows the relative coarseness of the sampling function. Few sample levels for a small signal corresponds to a low-fidelity (low SN_QR) encoding technique.

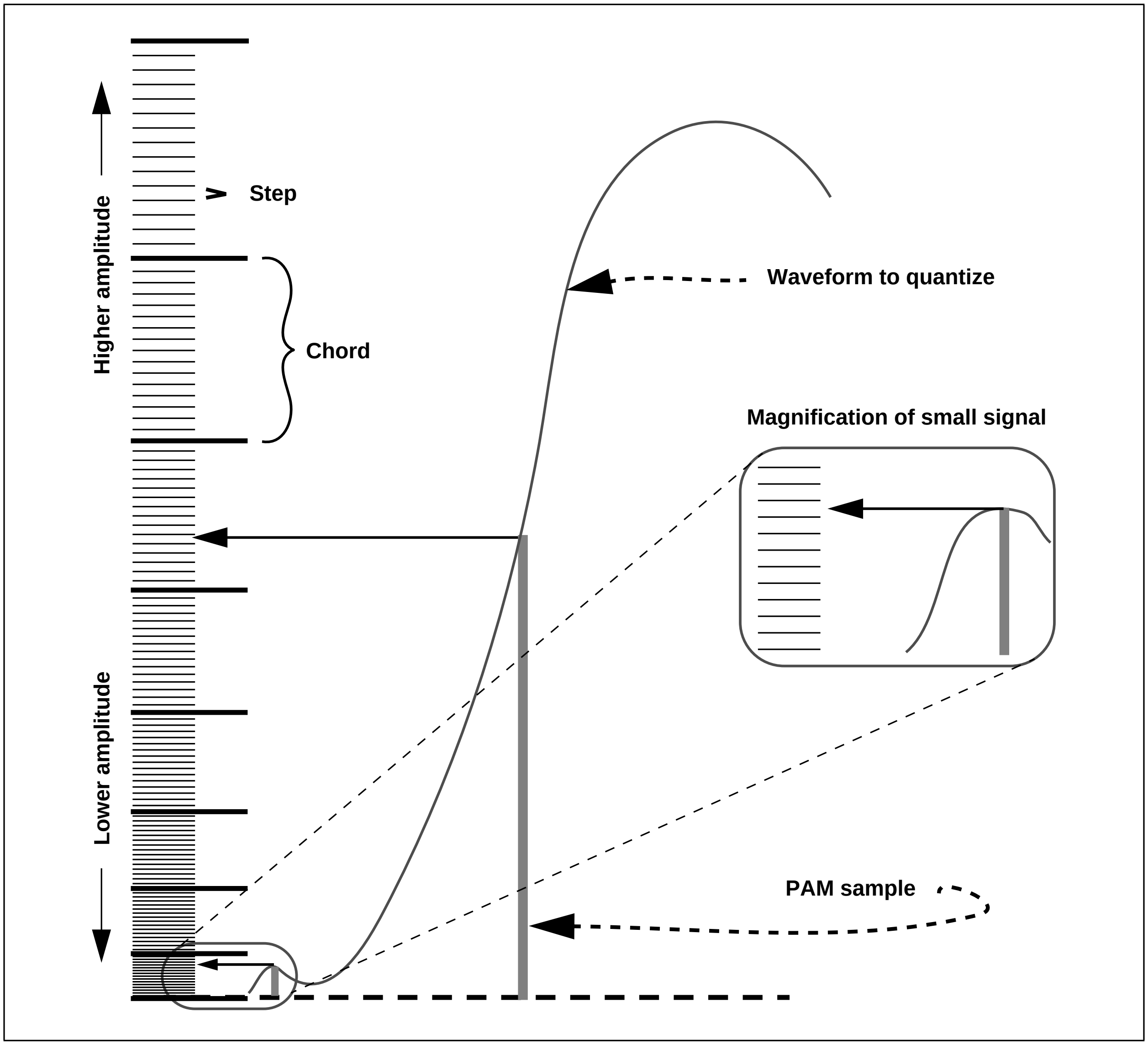

Figure 28: Logarithmic Quantization, another View

Figure 28 gives another view (as opposed to Figure 25) of a logarithmic quantizer process. The magnification of a low-amplitude region of the signal shows how sampling levels are close together, compared to the same low-amplitude signal quantized by linear encoding (see Figure 27). Smaller quantizing steps for low-amplitude signals allows a better signal-to-noise ratio, which amounts to better fidelity, when sampling voice signals.