ANALOG-DIGITAL CONVERSION

Walt Kester

Editor

ANALOG DEVICES

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CHAPTER 1
DATA CONVERTER HISTORY
Walt Kester

Chapter Preface

This chapter was inspired by Walt Jung's treatment of op amp history in the first chapter of his book, *Op Amp Applications* (Reference 1). His writing on the subject contains references to hundreds of interesting articles, patents, etc., which taken as a whole, paints a fascinating picture of the development of the operational amplifier—from Harold Black's early feedback amplifier sketch to modern high performance IC op amps.

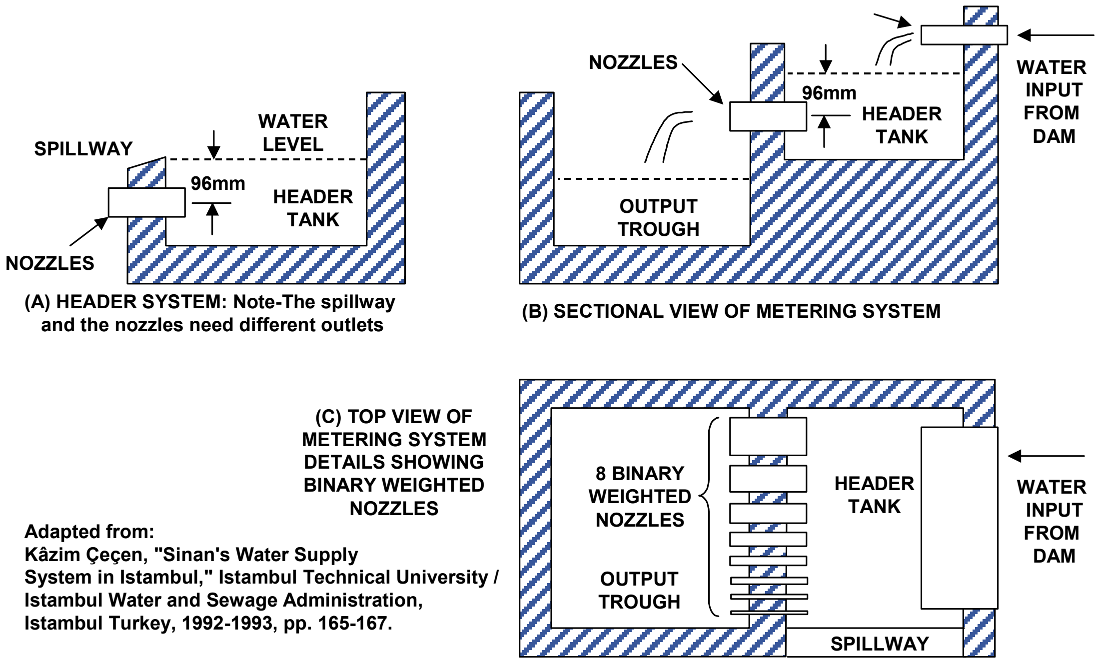
We have attempted to do the same for the history of data converters. In considering the scope of this effort—and the somewhat chaotic and fragmented development of data converters—we were faced with a difficult challenge in organizing the material. Rather than putting all the historical material in this single chapter, we have chosen to disperse some of it throughout the book. For instance, most of the historical material related to data converter architectures is included in Chapter 3 *(Data Converter Architectures)* along with the individual converter architectural descriptions. Likewise, Chapter 4 *(Data Converter Process Technology)* includes most of the key events related to data converter process technology. Chapter 5 *(Testing Data Converters)* touches on some of the key historical developments relating to data converter testing.

In an effort to make each chapter of this book stand on its own as much as possible, some of the historical material is repeated in several places—therefore, the reader should realize that this repetition is intentional and not the result of careless editing.

SECTION 1.1: EARLY HISTORY

It is difficult to determine exactly when the first data converter was made or what form it took. The earliest recorded binary DAC known to the authors of this book is not electronic at all, but hydraulic. Turkey, under the Ottoman Empire, had problems with its public water supply, and sophisticated systems were built to meter water. One of these is shown in Figure 1.1 and dates to the 18^{th} Century. An example of an actual dam using this metering system was the Mahmud II dam built in the early 19^{th} century near Istambul and described in Reference 2.

The metering system used reservoirs (labeled *header tank* in the diagrams) maintained at a constant depth (corresponding to the reference potential) by means of a spillway over which water *just* trickled (the criterion was sufficient flow to float a straw). This is illustrated in Figure 1.1A. The water output from the header tank is controlled by gated binary-weighted *nozzles* submerged 96 mm below the surface of the water. The output of the nozzles feeds an *output trough* as shown in Figure 1.1B. The nozzle sizes corresponded to flows of binary multiples and sub-multiples of the basic unit of 1 lüle (= 36 l/min or 52 m^3/day). An eight-lüle nozzle was known as a "sekizli lüle," a four lüle nozzle a "dörtlü lüle," a ¼ lüle nozzle a "kamuş," an eighth lüle a "masura," and a thirty-second lüle a "çuvaldiz." Details of the metering system using the binary weighted nozzles are shown in Figure 1.1C. This is functionally an 8-bit DAC with manual (rather than digital, no doubt) input and a wet output, and it may be the oldest DAC in the world. There are probably other examples of early data converters, but we will now turn our attention to those based on more familiar electronic techniques.



Adapted from:
Kâzim Çeçen, "Sinan's Water Supply System in Istanbul," Istanbul Technical University / Istambul Water and Sewage Administration, Istambul Turkey, 1992-1993, pp. 165-167.

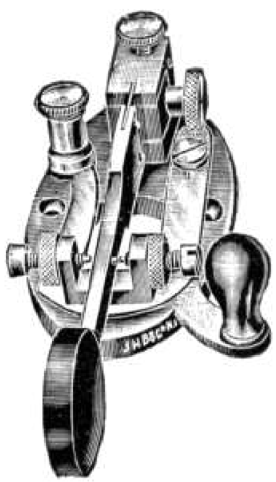
Figure 1.1: *Early 18th Century Binary Weighted Water Metering System*

Probably the single largest driving force behind the development of electronic data converters over the years has been the field of communications. The telegraph led to the invention of the telephone, and the subsequent formation of the Bell System. The proliferation of the telegraph and telephone, and the rapid demand for more capacity, led to the need for multiplexing more than one channel onto a single pair of copper conductors. While time division multiplexing (TDM) achieved some measure of popularity, frequency division multiplexing (FDM) using various carrier-based systems was by far the most successful and widely used. It was pulse code modulation (PCM), however, that put data converters on the map, and understanding its evolution is where we begin.

The material in the following sections has been extracted from a number of sources, but K. W. Cattermole's classic 1969 book, *Principles of Pulse Code Modulation* (Reference 3), is by far the most outstanding source of historical material for both PCM and data converters. In addition to the historical material, the book has excellent tutorials on sampling theory, data converter architectures, and many other topics relating to the subject. An extensive bibliography cites the important publications and patents behind the major developments. In addition to Cattermole's book, the reader is also referred to an excellent series of books published by the Bell System under the title of *A History of Engineering and Science in the Bell System* (References 4 through 8). These Bell System books are also excellent sources for background material on the entire field of communications.

The Early Years: Telegraph to Telephone

According to Cattermole (Reference 3), the earliest proposals for the electric telegraph date from about 1753, but most actual development occurred from about 1825-1875. Various ideas for binary and ternary numbers, codes of length varying inversely with probability of occurrence (Schilling, 1825), reflected-binary (Elisha Gray, 1878—now referred to as the *Gray* code), and chain codes (Baudot, 1882) were explored. With the expansion of telegraphy came the need for more capacity, and multiplexing more than one signal on a single pair of conductors. Figure 1.2 shows a typical telegraph key and some highlights of telegraph history.

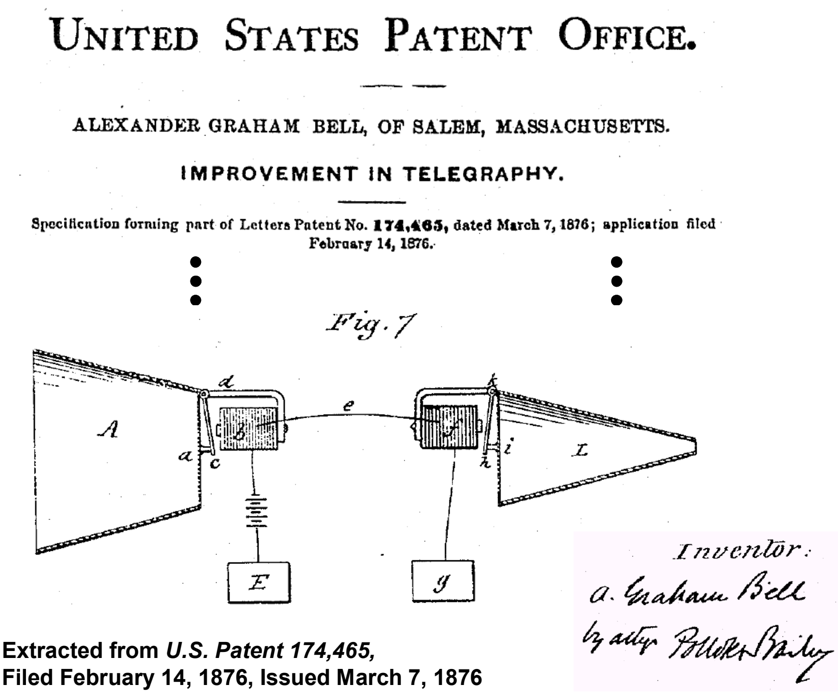


- **Telegraph proposals: Started 1753**
- **Major telegraph development: 1825 - 1875**
- **Various binary codes developed**
- **Experiments in multiplexing for increased channel capacity**
- **Telephone invented: 1875 by A. G. Bell while working on a telegraph multiplexing project**
- **Evolution:**
  - **Telegraph: Digital**
  - **Telephone: Analog**
  - **Frequency division multiplexing (FDM): Analog**
  - **Pulse code modulation (PCM): Back to Digital**

Figure 1.2: *The Telegraph*

The invention of the telephone in 1875 by Alexander Graham Bell (see References 9 and 10) was probably the most significant event in the entire history of communications. It is interesting to note, however, that Bell was actually experimenting with a telegraph multiplexing system (Bell called it the *harmonic* telegraph) when he recognized the possibility of transmitting the voice itself as an analog signal.

Figure 1.3 shows a diagram from Bell's original patent which puts forth his basic proposal for the telephone. Sound vibrations applied to the transmitter *A* cause the membrane *a* to vibrate. The vibration of *a* causes a vibration in the armature *c* which induces a current in the wire *e* via the electromagnet *b*. The current in *e* produces a corresponding fluctuation in the magnetic field of electromagnet *f*, thereby vibrating the receiver membrane *i*.



Extracted from *U.S. Patent 174,465*,
Filed February 14, 1876, Issued March 7, 1876

Figure 1.3: *The Telephone*

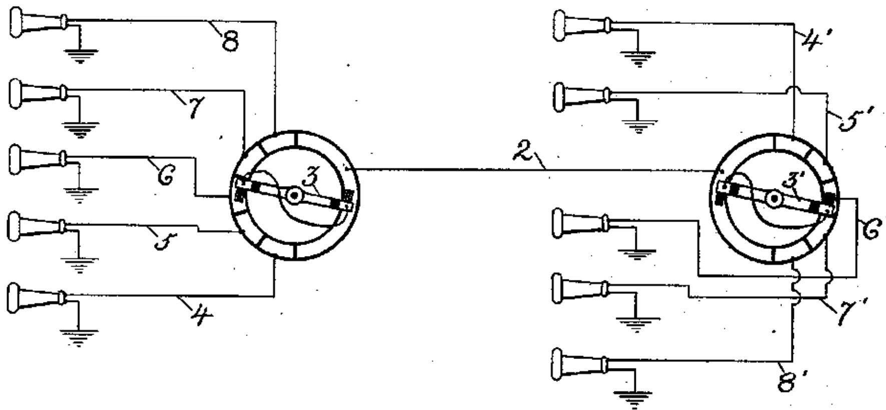
The proliferation of the telephone generated a huge need to increase channel capacity by multiplexing. It is interesting to note that studies of multiplexing with respect to telegraphy led to the beginnings of information theory. Time division multiplexing (TDM) for telegraph was conceived as early as 1853 by a little known American inventor, M. B. Farmer; and J. M. E. Baudot put it into practice in 1875 using rotating mechanical commutators as multiplexers.

In a 1903 patent (Reference 11), Willard M. Miner describes experiments using this type of electromechanical rotating commutator to multiplex several analog telephone conversations onto a single pair of wires as shown in Figure 1.4. Quoting from his patent, he determined that each channel must be sampled at

"... a frequency or rapidity approximating the frequency or average frequency of the finer or more complex vibrations which are characteristic of the voice or of articulate speech, ..., as high as 4320 closures per second, at which rate I find that the voice with all its original timbre and individuality may be successfully reproduced in the receiving instrument. ... I have also succeeded in getting what might be considered as commercial results by using rates of closure that, comparatively speaking, are as low as 3500 closures per second, this being practically the rate of the highest note which characterizes vowel sounds."

At higher sampling rates, Miner found no perceptible improvement in speech quality, probably because of other artifacts and errors in his rather crude system.

There was no follow-up to Miner's work on sampling and TDM, probably because there were no adequate electrical components available to make it practical. FDM was well established by the time adequate components did arrive.



Extracted from: Williard M. Miner, "Multiplex Telephony," ***U.S. Patent 745,734,***
Filed February 26, 1903, Issued December 1, 1903

Figure 1.4: *One of the Earliest References to a Criteria for Determining the Sampling Rate*

The Invention of PCM

Pulse code modulation was first disclosed in a relatively obscure patent issued to Paul M. Rainey of Western Electric in 1921 (Reference 12). The patent describes a method to transmit facsimile information in coded form over a telegraph line using 5-bit PCM. The figure from the patent is shown in Figure 1.5 (additional labels have been added for clarity).

Rainey proposed that a light beam be focused on the transparency of the material to be transmitted. A photocell is placed on the other side of the transparency to gather the light and produce a current proportional to the intensity of the light. This current drives a galvanometer which in turn moves another beam of light which activates one of 32 individual photocells, depending upon the amount of galvanometer deflection. Each individual photocell output activates a corresponding relay. The five relay outputs are connected in such a way as to generate the appropriate code corresponding to the photocell location. The digital code is thus generated from an "m-hot out of 32 code" , similar to modern flash converters. The output of this simple electo-optical-mechanical "flash" converter is then transmitted serially using a rotating electromechanical commutator, called a distributor.

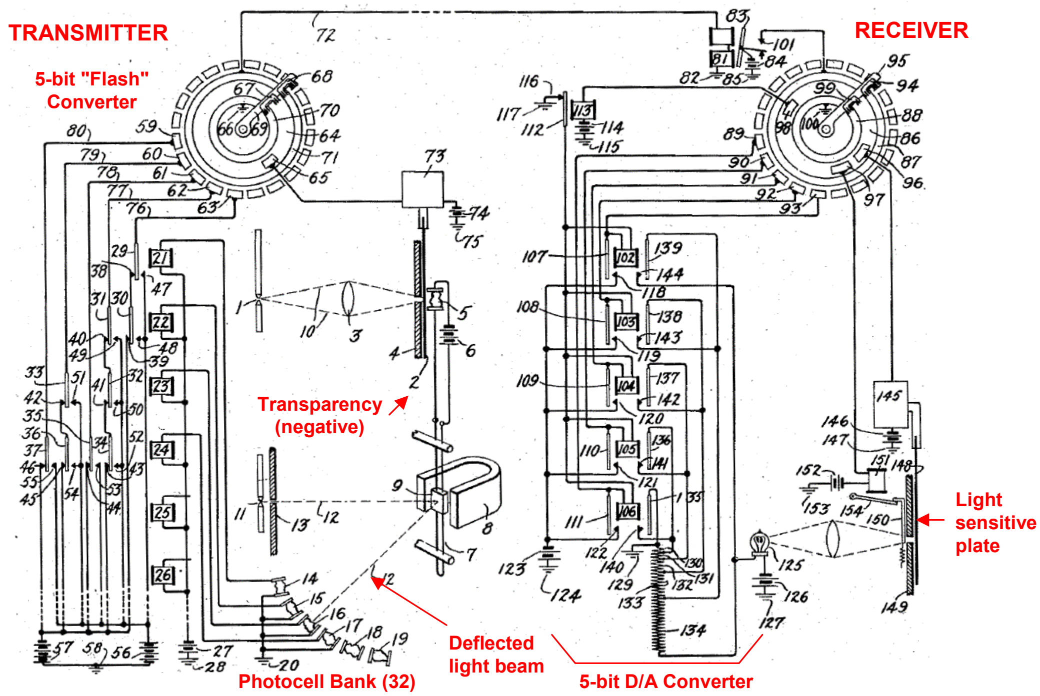


Figure 1.5: *The First Disclosure of PCM: Paul M. Rainey, "Facimile Telegraph System," U.S. Patent 1,608,527, Filed July 20, 1921,Issued November 30, 1926*

The serial data is transmitted, received, and converted into a parallel format using a second distributor and a bank of relays. The received code determines the combination of relays to be activated, and the relay outputs are connected across appropriate taps of a resistor which is in series with the receiving lamp. The current through the receiving lamp therefore changes depending upon the received code, thereby varying its intensity proportionally to the received code and performing the digital-to-analog conversion. The receiving lamp output is focused on a photographically sensitive receiving plate, thereby reproducing the original image in quantized form.

Rainey's patent illustrates several important concepts: quantization using a flash A/D converter, serial data transmission, and reconstruction of the quantized data using a D/A converter. These are the fundamentals of PCM. However, his invention aroused little interest at the time and was, in fact, forgotten by Bell System engineers. His patent was discovered years later after many other PCM patents had already been issued.

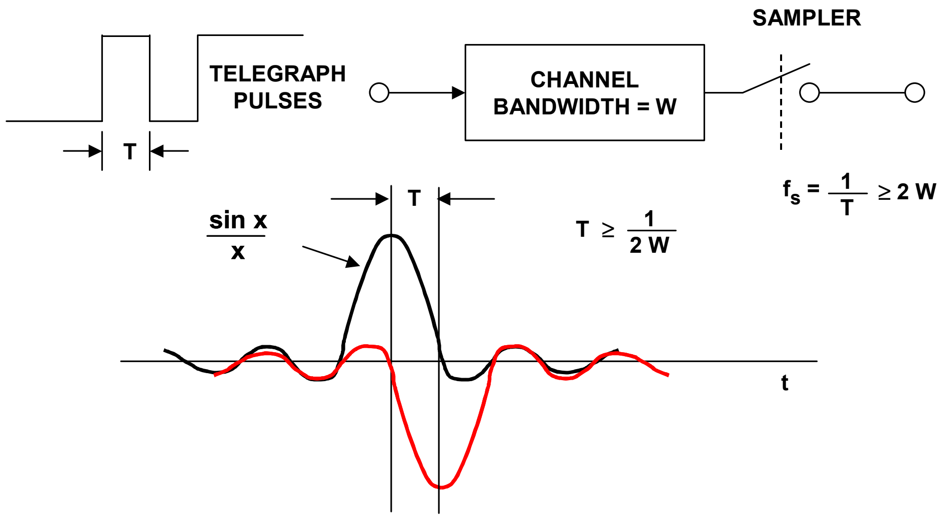
The Mathematical Foundations of PCM

In the mid-1920's, Harry Nyquist studied telegraph signaling with the objective of finding the maximum signaling rate that could be used over a channel with a given bandwidth. His results are summarized in two classic papers published in 1924 (Reference 13) and 1928 (Reference 14), respectively.

In his model of the telegraph system, he defined his signal as:

$$s(t) = \sum_k a_k f(t - kT). \qquad \text{Eq. 1.1}$$

In the equation, f(t) is the basic pulse shape, a_k is the amplitude of the kth pulse, and T is the time between pulses. DC telegraphy fits this model if f(t) is assumed to be a rectangular pulse of duration T, and a_k equal to 0 or 1. A simple model is shown in Figure 1.6. The signal is bandlimited to a frequency W by the transmission channel.



- Up to 2W pulses per second can be transmitted over a channel which has a bandwidth W.
- If a signal is sampled instantaneously at regular intervals at a rate at least twice the highest significant signal frequency, then the samples contain all the information in the original signal.

Figure 1.6: *Harry Nyquist's Classic Theorem: 1924*

His conclusion was that the pulse rate, 1/T, could not be increased beyond 2W pulses per second. Another way of stating this conclusion is *if a signal is sampled instantaneously at regular intervals at a rate at least twice the highest significant signal frequency, then the samples contain all the information in the original signal*. This is clear from Figure 1.6 if the filtered rectangular pulses are each represented by a sinx/x response. The sinx/x time domain impulse response of an ideal lowpass filter of bandwidth W has zeros at intervals of 1/2W. Therefore, if the output waveform is sampled at the points indicated in the diagram, there will be no interference from adjacent pulses, provided $T \geq 1/2W$ (or more commonly expressed as: $f_S \geq 2W$), and the amplitude of the individual pulses can be uniquely recovered.

Except for a somewhat general article by Hartley in 1928 (Reference 15), there were no significant additional publications on the specifics of sampling until 1948 in the classic papers by Shannon, Bennett, and Oliver (References 16-19) which solidified PCM theory for all time. A summary of the classic papers on PCM is shown in Figure 1.7.

- **Multiplexing experiments such as Williard Miner, "Multiplex Telephony," U.S. Patent 745,734, filed February 26, 1903, issued December 1, 1903.**
- **H. Nyquist, "Certain Factors Affecting Telegraph Speed," Bell System Technical Journal, Vol. 3, April 1924, pp. 324-346.**
- **H. Nyquist, Certain Topics in Telegraph Transmission Theory, A.I.E.E. Transactions, Vol. 47, April 1928, pp. 617-644.**
- **R.V.L. Hartley, "Transmission of Information," Bell System Technical Journal, Vol. 7, July 1928, pp. 535-563,.**

- **Note: Shannon's classic paper was written in 1948, well after the invention of PCM:**

- **C. E. Shannon, "A Mathematical Theory of Communication," Bell System Technical Journal, Vol. 27, July 1948, pp. 379-423, and October 1948, pp. 623-656.**
- **W. R. Bennett, "Spectra of Quantized Signals," Bell System Technical Journal, Vol 27, July 1948, pp. 446-471.**
- **B. M. Oliver, J. R. Pierce, C. E. Shannon, "The Philosophy of PCM," IRE Proceedings, Vol. 36, November 1948, pp. 1324-1331.**
- **W. R. Bennett, "Noise in PCM Systems," Bell Labs Record, Vol. 26, December 1948, pp. 495-499**

Figure 1.7: *Mathematical Basis of PCM*

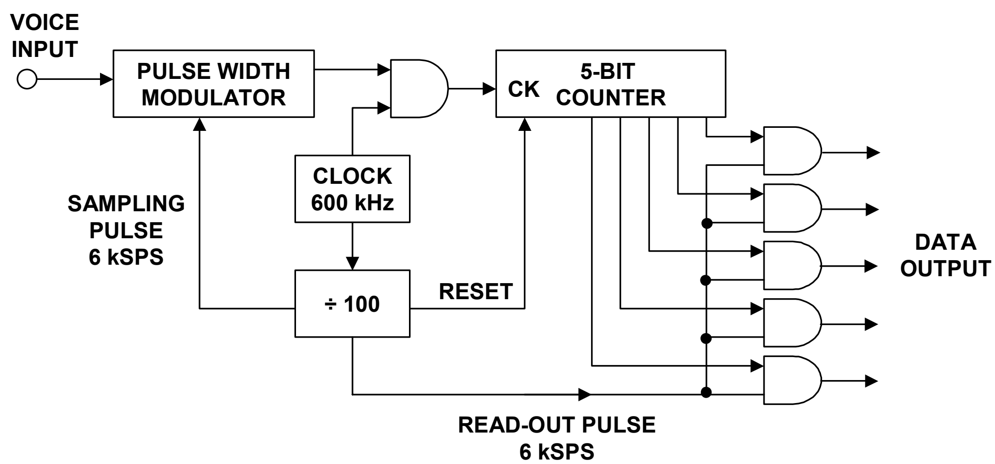
The PCM Patents of Alec Harley Reeves

By 1937, frequency division multiplexing (FDM) based on vacuum tube technology was widely used in the telephone industry for long-haul routes. However, noise and distortion were the limiting factors in expanding the capacity of these systems. Although wider bandwidths were becoming available on microwave links, the additional noise and distortion made them difficult to adapt to FDM signals.

Alec Harley Reeves had studied analog-to-time conversion techniques using pulse time modulation (PTM) during the beginning of his career in the 1920's. In fact, he was one of the first to make use of counter chains to accurately define time bases using bistable multivibrators invented by Eccles and Jordan a few years earlier. In PTM, the amplitude of the pulses is constant, and the analog information is contained in the relative timing of the pulses. This technique gave better noise immunity than strictly analog transmission, but Reeves was shortly to invent a system that would completely revolutionize communications from that point forward.

It was therefore the need for a system with the noise immunity similar to the telegraph system that led to the (re-) invention of pulse code modulation (PCM) by Reeves at the Paris labs of the International Telephone and Telegraph Corporation in 1937. The very first PCM patent by Reeves was filed in France, but was immediately followed by similar patents in Britain and the United States, all listing Reeves as the inventor (Reference 20). These patents were very comprehensive and covered the far-reaching topics of (1) general principles of quantization and encoding, (2) the choice of resolution to suit the noise and bandwidth of the transmission medium, (3) transmission of signals in digital format serially, in parallel, and as modulated carriers, and (4) a counter-based design for the required 5-bit ADCs and DACs. Unlike the previous PCM patent by Rainey in 1926, Reeves took full advantage of existing vacuum tube technology in his design.

The ADC and DAC developed by Reeves deserves some further discussion, since they represent one of the first all-electronic data converters on record. The ADC technique (see Figure 1.8) basically uses a sampling pulse to take a sample of the analog signal, set an R/S flip-flop, and simultaneously start a controlled ramp voltage. The ramp voltage is compared with the input, and when they are equal, a pulse is generated that resets the R/S flip-flop. The output of the flip-flop is a pulse whose width is proportional to the analog signal at the sampling instant. This pulse width modulated (PWM) pulse controls a gated oscillator, and the number of pulses out of the gated oscillator represents the quantized value of the analog signal. This pulse train can be easily converted to a binary word by driving a counter. In Reeves' system, a master clock of 600 kHz is used, and a 100:1 divider generates the 6-kHz sampling pulses. The system uses a 5-bit counter, and 31 counts (out of the 100 counts between sampling pulses) therefore represents a fullscale signal.



Adapted from: Alec Harley Reeves, "Electric Signaling System,"
***U.S. Patent 2,272,070*, Filed November 22, 1939, Issued February 3, 1942**

Figure 1.8: *A. H. Reeves' 5-bit Counting ADC*

The DAC uses a similar counter and clock source as shown in Figure 1.9. The received binary code is first loaded into the counter, and the R/S flip-flop is reset. The counter is then allowed to count upward by applying the clock pulses. When the counter overflows and reaches 00000, the clock source is disconnected, and the R/S flip-flop is set. The number of pulses counted by the encoding counter is thus the complement of the incoming data word. The output of the R/S flip-flop is a PWM signal whose analog value is the complement of the input binary word. Reeves uses a simple lowpass filter to recover the analog signal from the PWM output. The phase inversion in the DAC is easily corrected in either the logic or in an amplifier further down the signal chain.

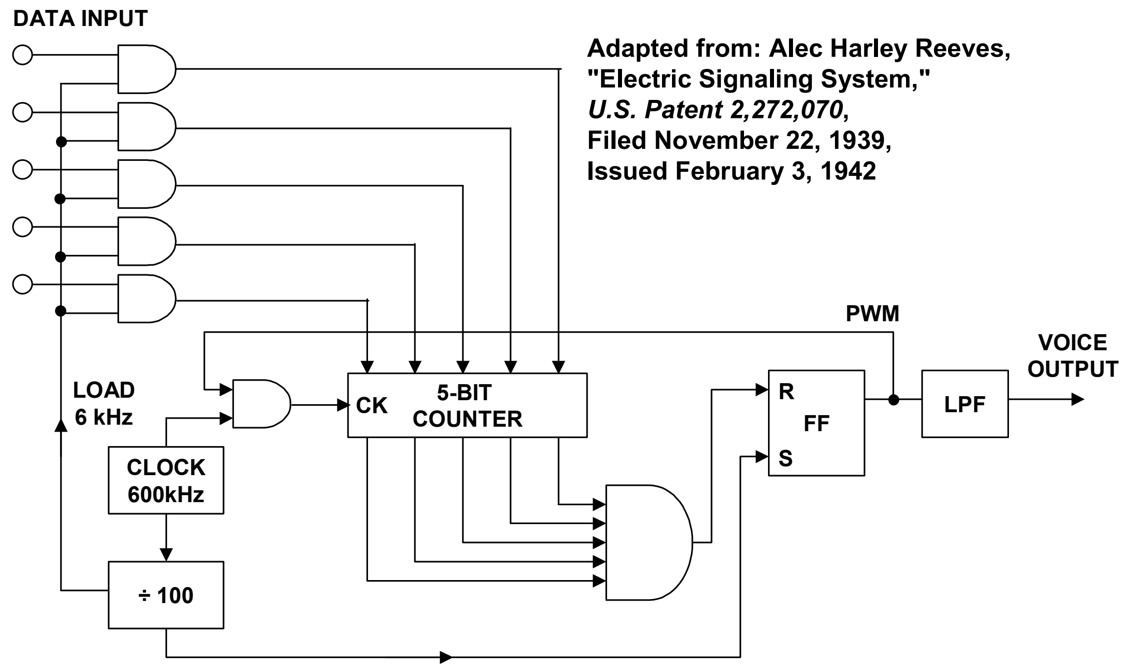


Figure 1.9: *A. H. Reeves' 5-bit Counting DAC*

Reeves' patents covered all the essentials of PCM: sampling, quantizing, and coding the digitized samples for serial, parallel, phase-modulated, and other transmission methods. On the receiving end, Reeves proposed a suitable decoder to reconstruct the original analog signal. In spite of the significance of his work, it is interesting to note that after the patent disclosures, Reeves shifted his attention to the shortwave transmission of speech using pulse-amplitude modulation, pulse-duration modulation, and pulse-position modulation, rather than pursuing PCM techniques.

PCM and the Bell System: World War II through 1948

Under a cross-licensing arrangement with International Telephone and Telegraph Corporation, Bell Telephone Laboratories' engineers reviewed Reeves' circuit descriptions and embarked upon their own pursuit of PCM technology. Starting in about 1940 and during World War II, studies were conducted on a speech secrecy system that made PCM techniques mandatory.

The highly secret "Project-X" to develop a speech secrecy system was started in 1940 by Bell Labs and is described in detail in Reference 6 (pp. 296-317). It used a complex technique based on vacuum tube technology that made use of the previously developed "vocoder," PCM techniques, and a unique data scrambling technique utilizing a phonograph recording containing the electronic "key" to the code. This system was designed at Bell Labs and put into production by Western Electric in late 1942. By April, 1943, several terminals were completed and installed in Washington, London, and North Africa. Shortly thereafter, additional terminals were installed in Paris, Hawaii, Australia, and the Philippines.

By the end of the war, several groups at Bell Labs were studying PCM; however most of the wartime results were not published until several years later because of secrecy issues. The work of H. S. Black, J. O. Edson, and W. M. Goodall were published in 1947-1948. (References 21, 22, and 23). Their emphasis was on speech encryption systems based on PCM techniques, and many significant developments came out of their work. A PCM system which digitized the entire voice band to 5-bits, sampling at 8 kSPS using a successive approximation ADC was described by Edson and Black (Reference 21 and 22). W. M. Goodall described an experimental PCM system in his classic paper based on similar techniques (Reference 23).

Some of the significant developments which came out of this work were the successive approximation ADC, the electron beam coding tube, the Shannon-Rack decoder, the logarithmic spacing of quantization levels (companding), and the practical demonstrations that PCM was feasible. The results were nicely summarized in a 1948 article by L. A. Meacham and E. Peterson describing an experimental 24-channel PCM system (Reference 24). A summary of PCM work done at Bell Labs through 1948 is shown in Figure 1.10.

- **"Project-X" voice secrecy system using PCM, 1940-1943.**
- **5-bit, 8kSPS successive approximation ADC**
- **Logarithmic quantization of speech (companding)**
- **Electron beam coding tube, 7-bit, 100kSPS**
- **"Shannon-Rack" decoder (DAC)**
- **Successful demonstration of experimental PCM terminals**
- **Theoretical PCM work expanded and published by Shannon**

- **Germanium transistor invented: 1947**

Figure 1.10: *Bell Laboratories' PCM Work: World War II through 1948.*

A significant development in ADC technology during the period was the electron beam coding tube shown in Figure 1.11. The tube described by R. W. Sears in Reference 25 was capable of sampling at 96 kSPS with 7-bit resolution. The basic electron beam coder concepts are shown in Figure 1.11 for a 4-bit device. The early tubes operated in the serial mode (Figure 1.11A). The analog signal is first passed through a sample-and-hold, and during the "hold" interval, the beam is swept horizontally across the tube. The Y-deflection for a single sweep therefore corresponds to the value of the analog signal from the sample-and-hold. The shadow mask is coded to produce the proper binary code, depending on the vertical deflection. The code is registered by the collector, and the bits are generated in serial format. Later tubes used a fan-shaped beam (shown in Figure 1.11B), creating the first electronic "flash" converter delivering a parallel output word.

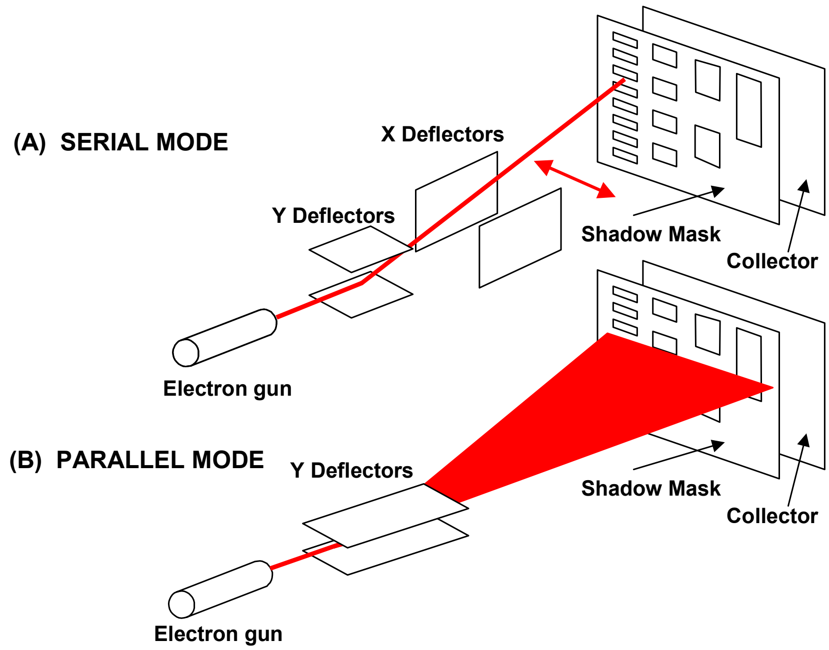


Figure 1.11: *The Electron Beam Coder*

Early electron tube coders used a binary-coded shadow mask, and large errors could occur if the beam straddled two adjacent codes and illuminated both of them. The way these errors occur is illustrated in Figure 1.12A, where the horizontal line represents the beam sweep at the midscale transition point (transition between code 0111 and code 1000). For example, an error in the most significant bit (MSB) produces an error of ½ scale. These errors were minimized by placing fine horizontal sensing wires across the boundaries of each of the quantization levels. If the beam initially fell on one of the wires, a small voltage was added to the vertical deflection voltage which moved the beam away from the transition region.

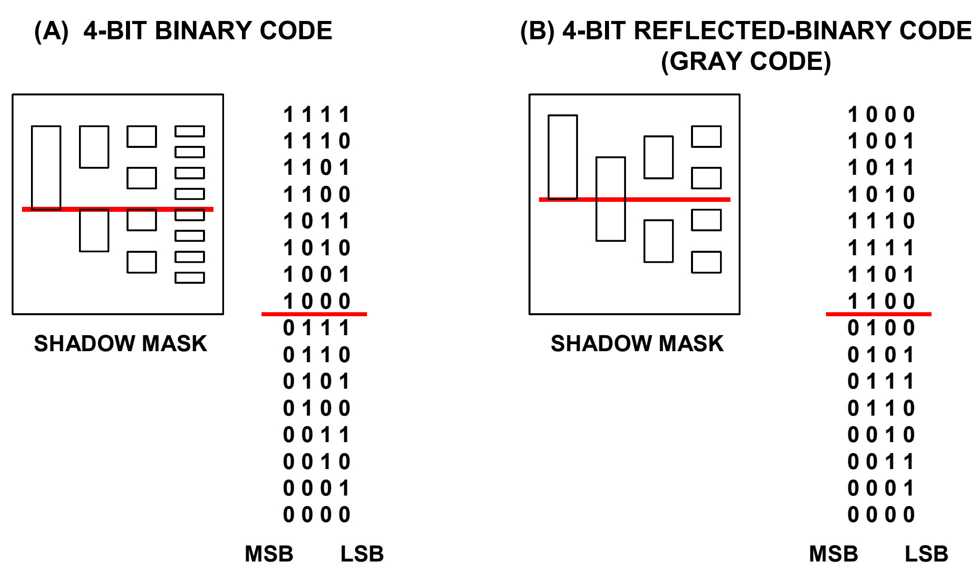


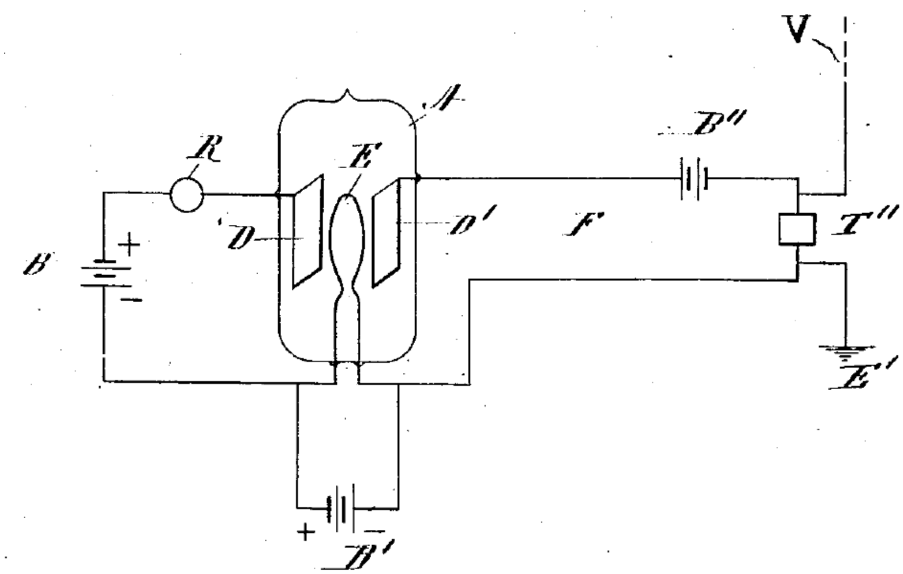
Figure 1.12: *Electron Beam Coder Shadow Masks*
for Binary and Gray Code

The errors associated with binary shadow masks were eliminated by using a Gray code shadow mask as shown in Figure 1.12B. This code was originally called the "reflected binary" code, and was invented by Elisha Gray in 1878, and later re-invented by Frank Gray in 1949 (see Reference 26). The Gray code has the property that adjacent levels differ by only one digit in the corresponding Gray-coded word. Therefore, if there is an error in a bit decision for a particular level, the corresponding error after conversion to binary code is only one least significant bit (LSB). In the case of midscale, note that only the MSB changes. It is interesting to note that this same phenomenon can occur in modern comparator-based flash converters due to comparator metastability. With small overdrive, there is a finite probability that the output of a comparator will generate the wrong decision in its latched output, producing the same effect if straight binary decoding techniques are used. In many cases, Gray code, or "pseudo-Gray" codes are used to decode the comparator bank output before finally converting to a binary code output (refer to Chapter 3 for further architectural descriptions).

In spite of the many mechanical and electrical problems relating to beam alignment, electron tube coding technology reached its peak in the mid-l960s with an experimental 9-bit coder capable of 12-MSPS sampling rates (Reference 27). Shortly thereafter, however, advances in solid-state ADC techniques quickly made the electron tube converter technology obsolete.

Op Amps and Regenerative Repeaters: Vacuum Tubes to Solid-State

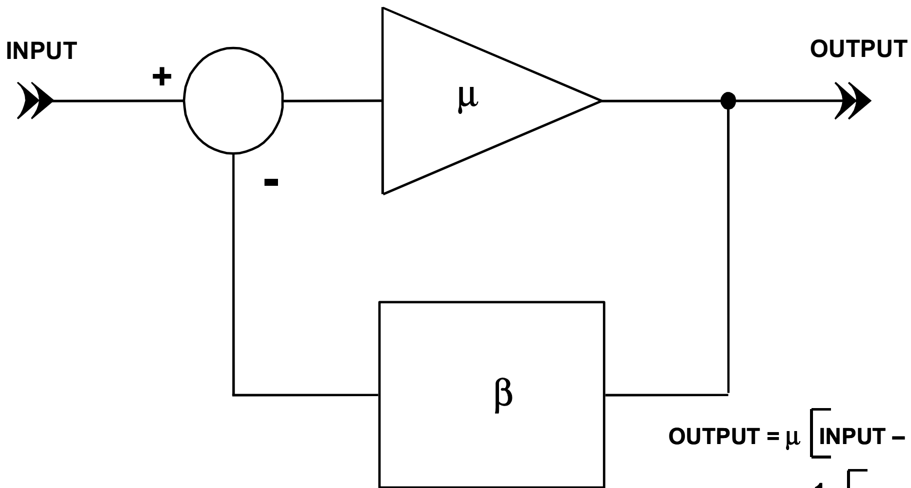
Except for early relatively inefficient electro-mechanical amplifiers (see Reference 5), electronic amplifier development started with the invention of the vacuum tube by Lee de Forest in 1906 (References 28 and 29). A figure from the original de Forest patent is shown in Figure 1.13.



Extracted from: Lee De Forest, "Device for Amplifying Feeble Electrical Currents," *U.S. Patent 841,387*, Filed October 25, 1906, Issued January 15, 1907

Figure 1.13: *The Invention of the Vacuum Tube: 1906*

By 1914, vacuum tube amplifiers had been introduced into the telephone plant. Amplifier development has always been critical to data converter development, starting with these early vacuum tube circuits. Key to the technology was the invention of the feedback amplifier by Harold S. Black in 1927 (References 30, 31, and 32). Amplifier circuit development continued throughout World War II, and many significant contributions came from Bell Labs. (The complete history of op amps is given in Reference 1). Figure 1.14 shows a drawing from a later article published by Black defining the feedback amplifier.



$$\text{OUTPUT} = \mu\left[\text{INPUT} - \beta \bullet \text{OUTPUT}\right]$$

$$\frac{\text{OUTPUT}}{\text{INPUT}} = \frac{1}{\beta}\left[\frac{1}{1+\frac{1}{\mu\beta}}\right]$$

Harold S. Black, "Stabilized Feedback Amplifiers,"
***Bell System Technical Journal*, Vol. 13, No. 1, January 1934**

Figure 1.14: *Harold Black's Feedback Amplifier of 1927*

The invention of the germanium transistor in 1947 (References 33, 34, and 35) was key to the development of PCM and all other electronic systems. In order for PCM to be practical, regenerative repeaters had to be placed periodically along the transmission lines. Vacuum tube repeaters had been somewhat successfully designed and used in the telegraph and voice network for a number of years prior to the development of the transistor, but suffered from obvious reliability problems. However, the solid state regenerative repeater designed by L. R. Wrathall in 1956 brought the PCM research phase to a dramatic conclusion (Reference 36). This repeater was demonstrated on an experimental cable system using repeater spacings of 2.3 miles on 19-gage cable, and 0.56 miles on 32-gauge cable. A schematic diagram of the repeater is reproduced in Figure 1.15.

The Wrathall repeater used germanium transistors designed by Bell Labs and built by Western Electric. The silicon transistor was invented in 1954 by Gordon Teal at Texas Instruments and gained wide commercial acceptance because of the increased temperature performance and reliability. Finally, the invention of the integrated circuit (References 37 and 38) in 1958 followed by the planar process in 1959 (Reference 39) set the stage for future PCM developments. These key solid state developments are summarized in Figure 1.16 and discussed in greater depth in Chapter 4 of this book.