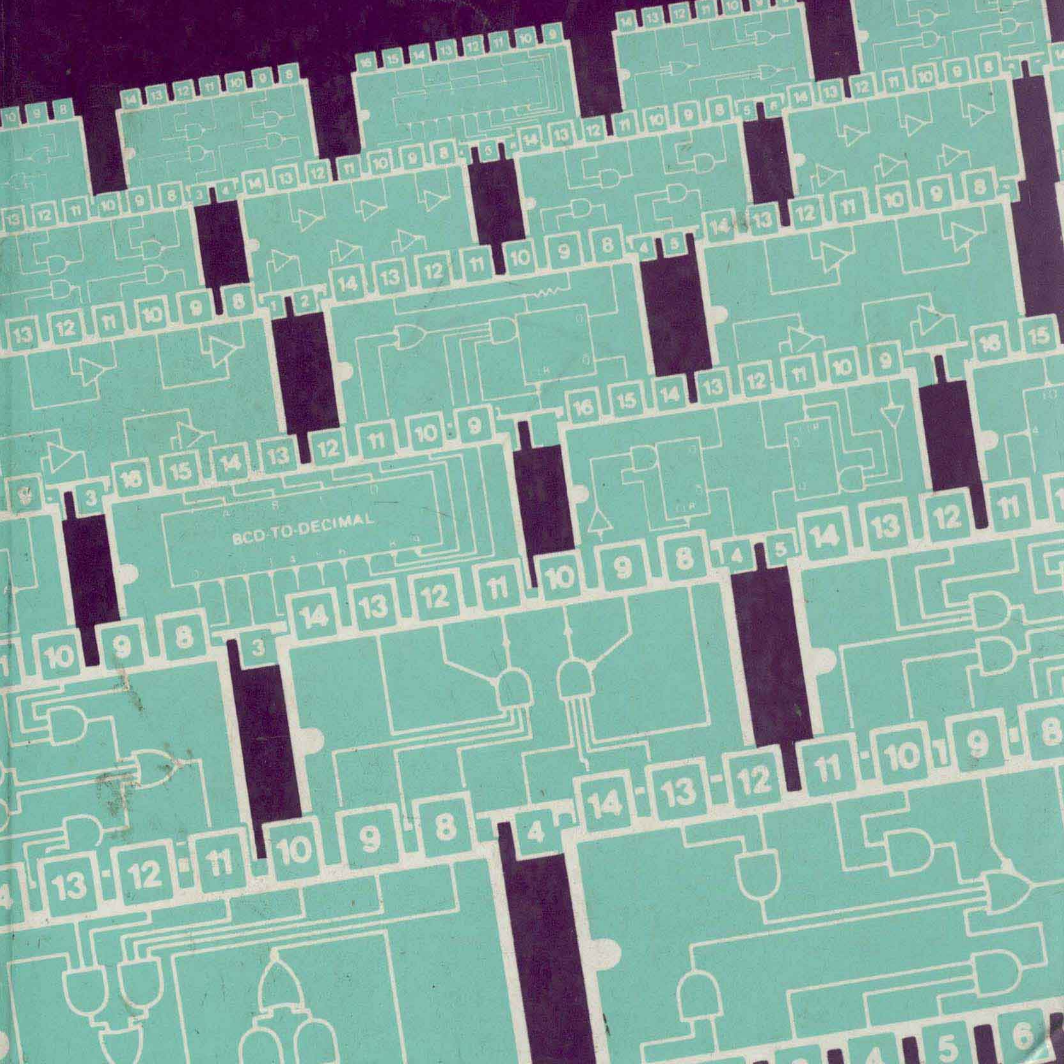
Ellis Horwood Series in
Electrical and Electronic Engineering

DIGITAL AND MICROPROCESSOR ENGINEERING

S. J. Cahill



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DIGITAL AND MICROPROCESSOR ENGINEERING

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To my wife Noreen, who has made everything worthwhile.

Preface

Digital electronic techniques have been around since before the electron was discovered. Historically the first commercial electronic system (defining the term electronic as pertaining to information processing by electrical means) was the electric telegraph. This communications system was based on a digital code devised by Samuel Morse around 1830. It was the harbinger of the coming electronic revolution of the 20th century.

The relay and allied electromagnetic switches remained the only significant electronic device for over 50 years. Thus the development of electromagnetic switching networks was of paramount importance; and indeed many ingenious mechanisms were patented in that period.

During the early 20th century the development of digital systems was overshadowed by analogue systems such as the telephone and wireless. Nevertheless some important work was done in applying switching networks to automatic telephone exchanges, railway signalling and similar applications. However, the most significant development was in the field of electromechanical business machines, which led shortly after the second world war to the stored-program computer.

Under the impetus of the digital computer, digital electronics and computer science became subjects in their own right. The rediscovery of Boolean algebra helped provide systematic design techniques. Digital implementation rapidly developed from relays through thermionic valves and diodes to transistors and integrated circuits. Together with the growth of electronic technologies came a subtle change in the role of the hardware designer. Up to the early 1960's most design tasks involved the extensive use of discrete components, which were used to build elementary digital elements such as gates and bistables. In practice this preoccupation with circuit design limited the complexity of the overall system.

With the use of transistors and the printed-circuit board some progress was made towards the concept of systems engineering, where design concentrated on interconnecting functional modules (often bought-in). This approach was accelerated with the introduction of SSI (gates and bistables); MSI (subsystems such as registers and arithmetic units) and LSI (subsystems such as memories and counter-timer chains).

The logical outcome of this trend is the provision of a complete system on a single integrated circuit. Although fabrication technology made this possible by the early 1970's, the economics of the profitable production of VLSI circuits is such that a large number of identical devices must be produced. By inference this requires a general-purpose system architecture. The interconnection pattern of a typical digital system shows little order, or correlation between systems. This random pattern makes the large-scale production of a general system IC difficult. To overcome this problem the fabrication vendors turned away from the essentially parallel operating random logic concept, to the structured serially operating bus-oriented computer architecture. The integrated bus controller and processing unit, known as a microprocessor, fulfills the role of a general-purpose system. The personality of a microprocessor-based system is imparted by storing code patterns in memory (which is itself regularily organised).

A typical digital system is a mix of structured programmable logic networks interfaced to random logic subsystems. Thus in order to efficiently implement current logic systems, the digital designer must be conversant with random logic, programmable logic and software. The objective of this text is to cover these topics in a progressive and unified manner.

The book commences with binary code patterns, from which the reader is taken through arithmetic algorithms, logic algebra, combinational and sequential circuit design. The treatment progresses from traditional design using SSI through MSI to LSI. The microprocessor is introduced and treated in a bottom-up fashion; as an extension to random logic design, rather than a top-down approach from computer science. This form of treatment enables the reader to design microprocessor chips into their circuit as a component, i.e. just another IC, rather than considering it as a small computer. It is in the area of dedicated logic systems that the majority of microprocessors are utilised, and it is in this application area that this approach is most applicable.

Throughout the book theory is illustrated with industrially standard devices. Within the available space, as many examples as possible are used to both introduce and extend the various concepts. Of necessity in ambitiously attempting to span the spectrum of digital design in a tutorially organised text, some topics are omitted or only briefly covered. For the same reason only one of the two standard general purpose 8-bit MPU families (6800 and 8080) is covered. I make no apology for this, as a review of all available devices is confusing in an introductory text.

If the reader uses this text in the spirit it was written, the field of specialist literature will be open to him/her. If the same reader gains a fraction of what I have learned in the writing of this text, I will consider the book as a success.

S. J. CAHILL Ulster Polytechnic, December 1981.

CHAPTER 1

Introduction

1.1 WHAT IS DIGITAL DATA?

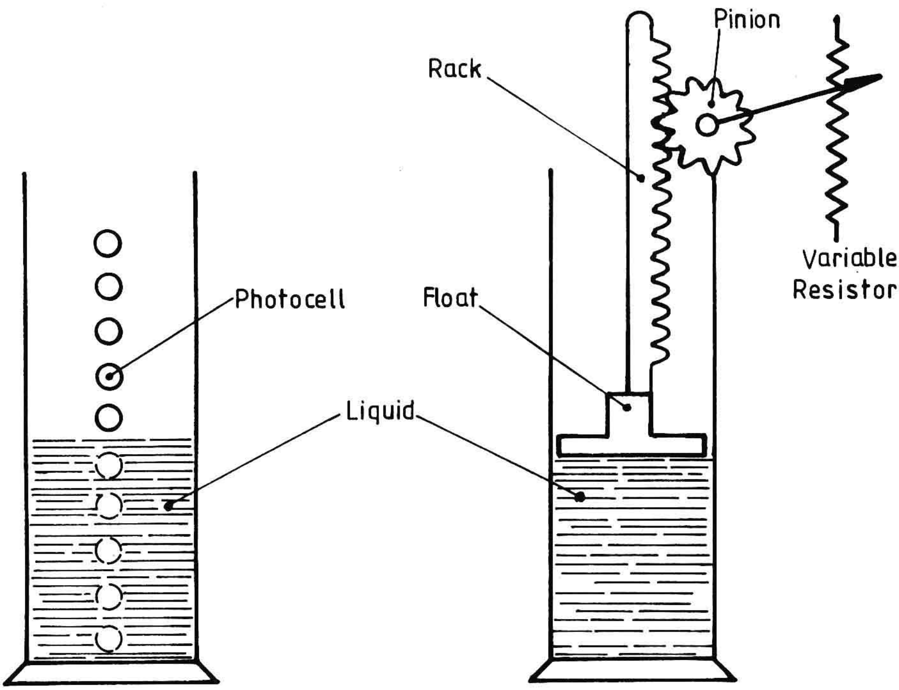
In our everyday dealings with the world, we naturally use digital concepts and manipulations. The vast majority of our representations of quantities involve the use of digits, usually in the form of patterns of ten possible digit values known as the decimal system. To appreciate the role of digital techniques in electronic engineering one needs a basic understanding of the two types of electrical signal representation, viz. analogue and digital.

1.1.1 Digital Versus Analogue Systems

This book is concerned primarily with the processing of electronic data represented in a digital form. The manipulation of data depends radically on whether it is in analogue or digital form.

The IEEE *Dictionary of Electrical and Electronics Terms* [1] defines the adjective **digital** as pertaining to data in the form of digits, i.e. implying data represented with discrete states. **Analogue**, on the other hand, pertains to data in the form of continuously variable physical quantities. The information content of an analogue signal lies in the value of some constituent parameter, such as its amplitude, frequency, or phase. Digital signals convey their information in the form of arrangements of discrete digits. Processing such signals essentially consists of pattern manipulation. The particular system output pattern existing at any one time depends on the input pattern, past and/or present, in a defined way.

As an example illustrating these concepts, consider the problem of measuring the level of a coloured fluid in a transparent tank, and transmitting the information electrically. One solution is to position a number of photocells at various heights, as shown in Fig. 1.1(a). Each of the ten cells is connected to a transmission link; and two values only are transmitted, representing light or dark. The pattern of the received data indicates the height. If we represent light by 0 and dark by 1, then for the diagram the received pattern will be 0000011111, a height of five units. Thus a specific pattern of digits represents a predetermined height. This particular digital system uses a **binary** notation. Binary means two, implying that only two digits are used, viz 0 and 1. It will be shown that using binary representations has peculiar advantages in electrical engineering, and practically all digital systems use this two-level scheme.



(a) Liquid obscures photocells. (b) Liquid alters a resistance value

Fig. 1.1. Two means of determining height of a liquid.

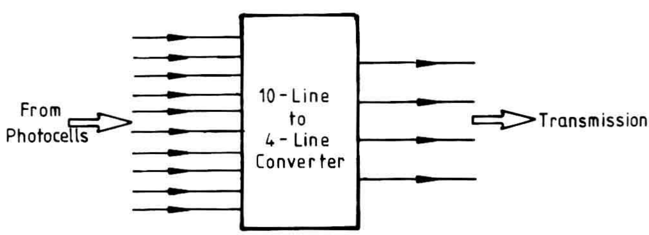
There are several points of interest which can be illustrated here, concerning the particular code (list of all patterns) used. This first point concerns the possibility of errors occurring. One of the major advantages of the binary system is the reduction of the possibility of error, as the receiver needs only to distinguish between two values. However, even with an enhanced noise immunity, transmission errors can occur; and there is always the possibility of failures occurring in some of the photocells. Consider a received pattern 0010011111, which is clearly in error, as it is a non-allowed or illegal code. Not only can certain errors be detected, but on the assumption that only a single error has occurred, the data may be corrected to read 0000011111. This process is a specific example of digital data processing, known as **error correction**.

The second point concerns the concept of **resolution** in electrical measurements. In this example the resolution, or minimum increment of discernment, is a tenth part of full scale. An increase in resolution using this code is only possible by using more photocells, and hence transmission paths.

In fact the code used for transmission is highly redundant, as only four binary digits can represent up to 16(2^4) different values. The table shown in Fig. 1.2(a) shows one of the many possibilities of transmitting the same data using only four lines. As ten levels have still to be detected, the same photocell array is required; but before transmission a stage of digital processing would be necessary to convert from one code to another, see Fig. 1.2(b). Each transmitted code depends uniquely on the input code only, and not on the past history of inputs. Such processing is known as **combinational**. If the outputs of a circuit depend on the sequence of input codes presented in time, then the processing is **sequential**.

10 - Line Code	4 - Line Code
0 0 0 0 0 0 0 0 0 0	0 0 0 0
0 0 0 0 0 0 0 0 0 1	0 0 0 1
0 0 0 0 0 0 0 0 1 1	0 0 1 0
0 0 0 0 0 0 0 1 1 1	0 0 1 1
0 0 0 0 0 0 1 1 1 1	0 1 0 0
0 0 0 0 0 1 1 1 1 1	0 1 0 1
0 0 0 0 1 1 1 1 1 1	0 1 1 0
0 0 0 1 1 1 1 1 1 1	0 1 1 1
0 0 1 1 1 1 1 1 1 1	1 0 0 0
0 1 1 1 1 1 1 1 1 1	1 0 0 1
1 1 1 1 1 1 1 1 1 1	1 0 1 0

(a) A more efficient code using only four lines



(b) A schematic of a code converter

Fig. 1.2. Increasing transmission efficiency.

One disadvantage in using a more efficient code is the reduction or loss of the error correcting facility, as the ratio of illegal to legal combinations is much smaller. Often codes are deliberately reduced in efficiency to introduce error detection/correction. In such cases systematic processing techniques exist to obtain the highest degree of efficiency consistent with the specified error protection capability. Error protection is discussed more fully in Chapter three.

If binary representation is abandoned for a decimal form, then only two transmission lines are needed, one for units and the other for the tens. If a decimal scheme is used, ten different parameter values, including zero, must be sent and detected, giving a corresponding reduction in error immunity. An alternative possibility would be to use a single line carrying eleven levels, with a consequent reduction in the ability to reject noise on the line.

Finally, returning to the binary case, multiple transmission lines were used, each carrying one digit position. Such a data transmission technique is known as **parallel.** As an alternative each digit position could be sampled and transmitted in turn. Providing the two commutator switches are held in synchronisation (Fig. 1.3), the complete pattern will eventually be received.

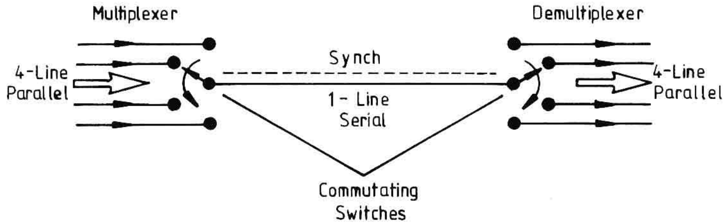


Fig. 1.3. Showing how parallel data may be sent serially using time division multiplexing.

Each digit as it is received can be stored in a memory cell or **flip flop**, capable of storing either the values 0 or 1. This method of data transmission is known as **serial**. It has the disadvantage of slowness, especially when each code pattern or **word** contains a large number of digits. Although both the transmitter and receiver are more complex, the use of the serial system is economically justified where the transmission path is long. The method of sequential sampling is known as **time division multiplexing.**

Figure 1.1(b) shows an alternative analogue height measurement scheme. A float operates a rack and pinion mechanism, which controls the value of a resistor. The change can be arranged to give a value of voltage proportional to height. This value is then sent along the line. The receiver could be a calibrated moving coil meter. The relative simplicity, as compared to digital systems, is greater than is illustrated here. This is because most quantities which are measured, such as height, pressure, speech, are naturally analogue. Employing digital transmission involves the use of an **analogue to digital conversion** process at the transmitter, and perhaps **digital to analogue conversion** at the receiver. An example of this is the sending of telephone speech data using digital techniques; known as **pulse code modulation** (PCM) [2].

Here the analogue speech waveform is sampled at regular intervals, and the value of each sample is encoded to binary form, and transmitted serially. At the receiver, each binary word is stored and converted back to analogue speech.

Analogue transmission by its nature is simple and cheap, has an infinite theoretical resolution, and needs only a single line per message. Why then are digital techniques now used in the majority of electronic data processing systems? The answer to this lies in two disadvantages of analogue representation.

The major transmission problem is the difficulty in providing an error protection capability. Consider our example of height measurement. If the analogue signal is to be sent over a telephone line, then from time to time the quality or attenuation of the path may change. If the attenuation of the line should change, then at the receiver it is difficult to determine whether the height has changed or the line conditions. With an analogue signal noise is cumulative, i.e. cannot be removed. Using a binary representation requires only the detection of two possibilities for each digit, to give the full designed (albeit limited) resolution. Any resolution may be obtained by increasing the number of digits. Allied to the transmission problem is the progressive deterioration of an analogue signal when processed by a system comprising many stages. Any noise or distortion is passed from one stage to the succeeding stage, which progressively impairs the quality of the signal.

The second major disadvantage of analogue signal processing is limited accuracy, as opposed to resolution. The resolution of an analogue signal is generally only limited by the sensitivity of the receiving apparatus, such as the eye. With the aid of a magnifying glass a moving coil meter could be read to better than 0.1% of full scale. However, the accuracy of the reading may only be 3% full scale deflection. This is because analogue processing demands a linear response for an infinite number of levels within the range, which is expensive and difficult to engineer. As a further example a 20-inch slide rule, where analogue lengths represent logarithms of numbers, cannot easily be read to a resolution of better than 0.1%.

This sets an upper boundary to the accuracy of the reading, and is attained only for a perfectly linear scale. The only limit to the accuracy of a digital electronic calculator, is that imposed by the number of digits used as the number representation.

In summary, digital systems can be said to cover that class of data processing which represents quantities as patterns of digits. A further subdivision is based on the number of different digits used in the representation. Two-digit schemes are by far the most common; and the terms digital and binary are often used synonymously. Digital processing possesses the advantages of noise immunity, in the broad sense including errors, and having a resolution which can easily be tailored to fit a particular requirement. It is presumably for these reasons that nerve signals are in a digital form.

Processing in digital systems is mainly concerned with pattern recognition and conversion; whilst in the case of analogue, amplification and frequency response tailoring. Analogue systems, whilst being poor from the point of view of both noise immunity and accuracy, are often cheaper to implement, and to maintain, if the specification is not too rigorous. Often it is possible to combine the advantages of both types in one system, by using a mixture of the two techniques, in so called **hybrid** circuits.

1.1.2 Number Systems

A considerable subset of digital systems deals with arithmetic operations. To understand the operation of this class of circuits, it is necessary to discuss the representation of numbers.

All modern number systems use the **radix** representation, which came to us from the Hindus [3] via Arabia. This format is based on the following ideas:

(1) The position of a symbol within a number indicates the multiplication by a relevant power of the base.
(2) A special symbol is used to represent nothing (zero).
(3) The number of different symbols is restricted to the base quantity.

All these ideas are contained in the familiar decimal system, which is base ten. For example the decimal number 1,908 is shorthand for 1×10^3 $(1 \times 1{,}000)$ plus 9×10^2 (9×100) plus 0×10^1 (0×10) plus 8×10^0 (8×1). The ten symbols are 0, 1, 2, 3, 4, 5, 6, 7, 8, and 9. Each digit's value in moving leftwards is increased by a multiplicative factor of ten. Thus it is not only the values of the symbols which are used to represent a quantity, but also their position. Numbers may be extended to fractional values by signifying positions to the right of the unity column as having negative powers of the base. Thus the number 3.142 reads 3×10^0 (3×1) plus 1×10^{-1} $(1 \times \frac{1}{10})$ plus 4×10^{-2} $(4 \times \frac{1}{100})$ plus 2×10^{-3} $(2 \times \frac{1}{1000})$. A (decimal) point is used to separate the integer and fractional parts of the number. Any decimal number may be represented as:

$$N_{10} = \sum_{i=-\infty}^{\infty} K_i \, 10^i$$

where K_i is the coefficient of the i^{th} power of ten.

Although historically, digital computers were built which used base-ten arithmetic [4,5], all current digital systems use base-two representations. This is due to the ease of fabricating arrays of switches, essentially two-state devices. The resulting binary notation is identical to decimal, but with each column signifying a power of two, and with only two symbols, viz 0 and 1. Thus any binary number can be represented as: