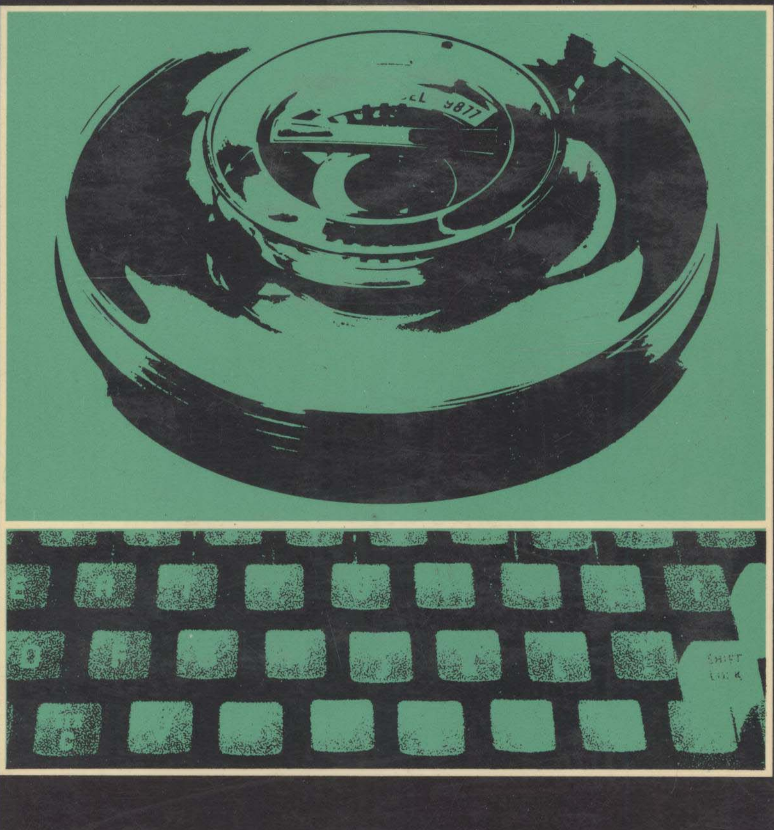
Second Edition

Digital Computer Structure and Design

R Townsend



Butterworths

Digital Computer Structure and Design

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R. TOWNSEND MSc(Eng), BSc(Eng), FIEE, SMIEEE

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Some men see things as they are and ask 'why?'
I dream of things that never were and ask 'why not?'

George Bernard Shaw

Preface to Second Edition

In the six years since this book was written there have been two major developments, which have radically changed the outlook of computer designers and users. These are the development of large semiconductor memories and microprocessors on a single chip. Both of these have emerged from the spectacular progress in the design of microcircuits.

Minicomputers have been largely eclipsed by the appearance of powerful microprocessors at astonishingly low prices. The small computers now in use are usually based on an internal microprocessor with input-output and peripheral devices.

Visual Display Units, which for some time had been regarded as the ideal general purpose input-output device, have at last reached the threshold of economic take-off, and are in common use. The more advanced examples of these also incorporate microprocessors.

The general use of the all conquering microprocessor does not absolve users from having some knowledge of the principles of what is happening inside, even though they may never need to design one. An understanding of the internal operations is also a help to programming. The organisation of a microprocessor is not very much different to that of the minicomputer. To a great extent, the microprocessor evolved from the minicomputer, by shrinking the whole circuit on to one silicon chip. Reduction of the word size to 8 bits leads to some changes, but the newer 16 bit microprocessors are getting back to the equivalent of a 16 bit minicomputer.

For this reason the organisation of a 16 bit minicomputer is still relevant to the present situation. In writing a book on computer design one either has to invent an architecture, or base it on an existing one, as has been done here, using the NOVA mincomputer as an example. The NOVA has a sound architecture and still provides a good basis on which to discuss the principles of computer design.

Chapter 1 has been revised to eliminate out-of-date material, and comments on the latest developments have been added.

In logic design the emphasis has moved from the design of actual processors to peripheral circuits, and special purpose logic into which microprocessors are embedded. This type of circuit is often unclocked, and requires the interfacing of synchronous and asynchronous systems. I have therefore added a section on asynchronous sequential circuits, as well as bringing Chapter 3 up-to-date in other respects.

Chapter 7 on computer memories has been entirely rewritten to provide an introduction to the various types of semiconductor memories. Their overwhelming success has rendered ferrite core memories almost completely obsolete.

Material has been added to Chapter 9 regarding large scale integrated arithmetic processors. The reference lists at the end of each Chapter have been completely revised.

I wish to give special thanks to Martin Gibson who carefully read the first edition and made invaluable comments for the revised edition.

Contents

Chapter 1

Introduction

In the light of the present day it may seem almost antediluvian to discuss the ancestry of the modern computer. However it may be of some interest to mention briefly how we arrived where we are now. Machines evolve like the natural world, and the present day microprocessor is descended from very different ancestors.

It used to be easy to distinguish calculators from computers, essentially the latter could be programmed and the former were keyboard machines, but now many calculators incorporate simple programming. Simple mechanical calculators were constructed by Pascal and others and culminated in complicated electromechanical machines in the 1940s.

Another line of descent can be found in the punched card machines, which can trace the idea of controlling a machine by holes in a card, or similar device, back to automatically controlled looms. These machines originated in the requirements for sorting and counting in the United States census. Later the concepts of the calculating machines were combined with the use of punched cards and evolved to produce a range of different machines which made possible elaborate automatic accounting systems and other applications.

The decisive step which seems to have resulted in the appearance on the scene of the digital computer as we now know it, was the introduction on the one hand of electronic counting and pulse handling techniques and on the other of the concept of the stored program. Both of these ideas were inherent in earlier work, but their tremendous potential had not been appreciated and they had not been clearly stated. Professor Babbage with the invention of his Analytical Engine in the 19th century had foreseen the possibilities and attempted to realise them mechanically, but his ideas were too far ahead of the technology of the time and he failed to complete the mechanical equivalent of a simple computer.

The technology of the first electronic digital computers was based on the vacuum tube and derived mainly from circuits developed in World War II in radar research and atomic energy work. Although these machines were made to work successfully there were severe limitations, particularly in size, heat dissipation and device reliability. The invention of the transistor occurred at an opportune time, and after a period of teething troubles, the first transistorised discrete circuit computers appeared in the late 1950s, due to demand for reduction in power consumption and size. Further need for reduction in size, heat dissipation, and reliability, stimulated by requirements of the armed services, has led to the evolution of microcircuit technology.

These advances have made possible the development of the giant 'number crunchers' having millions of individual circuits, each having a high enough reliability for the total aggregation to run for long periods, without failure, and having small enough power requirements that they can be reasonably housed without need of the elaborate cooling and air conditioning systems of the early computers.

At the other extreme the microprocessor has now appeared, having the capabilities and processing power in the latest devices of a medium size computer of several years ago. And all this in a device one can hold in the palm of the hand and costing only a few pounds.

Although the first effects of microcircuit technology have been felt at the smaller end of the computer range, their influence is now being felt in the design of large computers. Bit slice devices can be assembled to create processors with larger word sizes. Array processors have been designed using standard microprocessors, but it seems likely that special types may be designed to be used as elements of very large machines.

In parallel with developments in the design of processors, there has been much activity in memory design. Semiconductor memories have now superseded ferrite cores for the main computer memories, being used for both random access memories and read only memories.

The momentum of the computer industry has led to refinements and advances in many other technologies associated with computer engineering. The pace continues and there is the possibility in the future of the introduction into the computer art of new technologies such as Josephson junctions.

In distinction to the steady technological advance, the idea of a stored program, and in particular the storage of both numbers and instructions in the same memory in coded form, appeared as a strikingly new concept from which has developed the whole discipline of programming and software. Once the initial step had been taken the concepts of programming leading to assemblers, compilers and high level languages developed rapidly, although the realisation of these concepts in practical programming systems has proved a far more complex problem than was imagined.

Physical Description

A block diagram of the major components of a computer's system is shown in Figure 1.1. The Central Processing Unit (CPU) contains the main memory, the arithmetic unit and arithmetic registers, the control unit with its associated registers, and other control logic associated with the input-output bussing system. The CPU, usually housed in a somewhat undramatic series of cabinets, containing rows of cards with printed circuits, and transistors or integrated circuits, forms the hub of the system, and a large part of this book will be concerned with the organisation and design of the CPU.

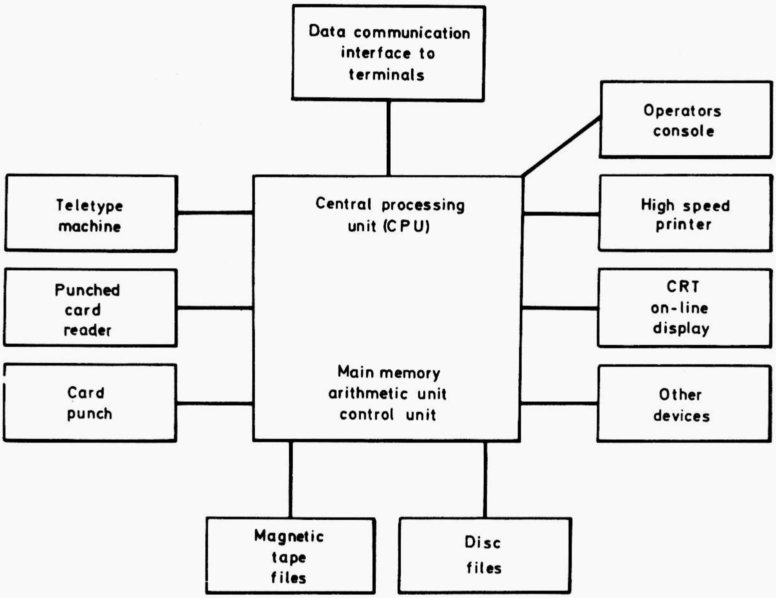

Figure 1.1 Block diagram of the major components of a computer system

Large machines may have, in addition to the CPU, one or many input-output processing units, which are dedicated to handling the many low level chores associated with input-output devices and release the CPU to devote the major part of its time to higher level calculations for which it is specialised.

Disposed around the central processor there will be a variety of peripheral devices. The operator's console usually now consists of a typewriter type keyboard and a visual display unit with a T.V. type tube. For service and debugging purposes, lights are sometimes provided to enable the display of the contents of various registers in the CPU, and switches allow the processor to be put into different operating modes such as Run, Single Operation, Single Step, as well as Manual Halt and Start. Because computers have now become very reliable, this maintenance console may be a separate portable device plugged in by a service man, and no longer ordinarily used by the operator.

A computer system may have some only of those shown in Figure 1.1, or possibly other input-output devices not shown attached to it including the following:

(a) *Visual Display Units* (VDU) are now the common means of communication by the operator even on small machines. Both graphical and alphanumeric data can be displayed. In larger systems there may be a number of VDUs in various parts of a building or remotely joined by a data communication system.

(b) A *Teletype Machine* enables one to type data and instructions to the computer via a typewriter keyboard, and the computer can also print information at a moderate rate to communicate with the operator. In addition it is possible to enter pre-punched data on punched paper tape, and also to receive data to be punched on paper tape for permanent retention.

(c) A *Punched Card Reader* for reading data into the computer from punched cards. Cards are a convenient medium for entering programs or data because it is easy to modify a few statements without having to repunch the whole program.

(d) In some cases a *Card Punch* is used, so that data can be punched in a form which can be read in conveniently at a later date. The tendency is to use these machines less as they are expensive, and programs can be stored now on disc files for short periods, or dumped on to magnetic tapes for longer term storage.

(e) Most larger installations have a *High Speed Printer* which allows data to be printed out rapidly in suitable format. This is especially important in commercial applications where large numbers of bills, invoices, pay slips, and cheques etc. must be printed.

(f) *CRT Displays* are used in more advanced systems for on-line operation with which there can be immediate man-machine interaction. Both graphical and alphanumeric data can be displayed. These will probably be used more in the future, when on-line communication with computers becomes more common.

(g) Mass storage is most commonly used in the form of magnetic tape or magnetic disc files at the present time. *Disc Files* have a large but limited capacity and have the advantage that any piece of data can be accessed fairly rapidly within a fraction of a second.

Magnetic Tape having its data stored in a linear arrangement on the tape, can be much slower in finding a particular piece of information, since the tape must be wound to that point. Since the reels of tape are removable it has the great advantage of unlimited storage capacity in reasonable volume, and is used for many semipermanent records.

(h) *Data Communications.* Some of the largest machines, for example the London University Control Data 7600 have systems for data communications, so that they can receive and transmit data to many remote terminals, and possibly other computers. This leads to the concept of a computer utility in which one can plug in to computing power in much the same way as one would plug into electric power or the telephone.

(i) The number of other devices which can be connected to a computer is almost unlimited and new uses are constantly arising.

Minicomputers

The overwhelming success of microprocessors has largely invaded the territory until recently assigned to machines that were styled minicomputers, although there has been a proliferation of smaller machines both for business and scientific purposes, but also for the computer hobbyist. They usually contain a microprocessor, plus extra semiconductor memory, and input output circuitry with a keyboard and some display device. The small size of these machines should not delude one as to their capability. The latest 16 bit microporcessors have a computing power which would have been considered respectable for a medium sized computer, not many years ago.

Special Purpose Computers

Because of the low cost of microprocessors, special purpose processors now tend to be designed with microprocessors embedded in specially designed pre-processing logic and linear circuits. The program, which is fixed, is stored in PROM s (Programmable Read Only Memories) and a small RAM (Random Access Memory) serves for data manipulation.

Computer Applications

Scientific Calculation The first computers were designed by laboratories and universities to enable them to attack mathematical problems, which would have been too laborious to solve manually due to the sheer calculating effort required. The original stimulus that led to the development of ENIAC and later UNIVAC was the need to calculate ballistic tables during World War II. Scientific enterprises generated the need for the solution of simultaneous equations, and differential and algebraic equations.

Statistical Studies The evaluation of statistical studies on the many aspects of our complex life in today's industrial society requires the processing of vast amounts of data obtained from sampling, which would not have been possible without modern computers.

Simulation It is possible to write a program to make a mathematical model of either a physical system, or an operational problem. For example it is possible to design a mathematical model of the arrival, unloading and loading and departure of ships in port. By varying parameters in the model, the operation of the existing installation may be optimised to maximise the traffic or minimise the cost. The same computer might be used to study a tidal model of the estuary to find the best way to channel the river and tidal flow to remove the hazards of sandbanks. Alternatively, the motion of a ship in the water can be modelled and the shape of the hull changed to find the best compromise in design to optimise the ship's performance under the expected conditions.

A notable improvement in the performance of lenses has been achieved due to the ability to model the lens on a computer and by the use of ray tracing optimise the lens design. In all these cases it is possible to discover the effects of changes in the environment or the design without the necessity of actually making the changes, or building many experimental designs.

Accounting The largest application of computers at present is in handling the vast load of accounting work generated in modern industrial organisations. Typical examples are the calculation of the payroll, invoicing, billing and interdepartmental transactions. Banks use computers to lighten the load of the increased flow of money throughout the nation and internationally. Automatic sorting and handling of cheques has become possible by the invention of machines which can directly read branch numbers and account numbers printed on the cheques in special characters.

Reservation Systems The world's airlines use giant computers with world-wide on-line communications to keep track of the reservations and available seats on planes removing the need for flying planes with unnecessary empty seats or the confusion of overbooking.

Controllers It would be difficult to enumerate the diverse variety of control applications in which computers can be applied. They are being used in London and Toronto to control and optimise the flow of road traffic throughout the city. Input sensors at various points continuously monitor vehicles, and taking the overall situation into account, they can modify and divert the traffic to maintain smooth flow and reduce jams.

Oil refineries and petrochemical plants need the continual monitoring and control of variables throughout the plant to maintain them in a safe and stable operation and to optimise the final products. Computers are used to continuously compute the optimum conditions, control variables, issue warnings and even take emergency action if necessary.

On a small scale the minicomputer is entering into everyday use in applications such as instrument control and processing of data, and apparently trivial occupations such as controlling of lighting in large factories, control of lifts in large buildings etc.

Communications It could be argued that the automatic telephone exchange was one of the first computers. Telephone exchanges are now becoming electronic and provide a good example of a special purpose computer designed for the specific application of remembering and routing telephone calls in the optimum way. They require less power and maintenance and are more reliable than the older electromechanical systems.

Computer Aided Design When a design procedure is well understood, whether it be the design of a building structure or bridge, or an electronic circuit, a program can be devised to obviate much of the labour associated. On large projects it also allows the possibility of many trial designs and the choice of the best by varying the parameters based on known factors.

Data Retrieval Computers can be provided with batteries of mass storage devices which make it possible to store and retrieve data at short notice, for example all known chemical compounds and their properties, for all National Health patients, and their health records, or the history of traffic offenders.

Computer technology has placed a powerful instrument in the hands of society, and it is up to us all to control its use for maximum benefit to the world.

The arrival of the low cost microprocessor has resulted in innumerable applications, which would not have been envisaged until recently. Many instruments now incorporate microprocessors as part of the circuitry, and they are becoming popular in T.V. games, and such things as controllers for sewing machines, washing machines and even toys.

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Chapter 2

Switching Theory

Logic Elements

The basic element from which the control system and arithmetic unit of a computer are built is the gate. By interconnecting various types of gates the required binary logical functions needed for computation and control of the computer can be obtained.

The study of the properties of interconnected networks of gates is called switching theory. Switching theory, unlike circuit theory, does not have its basis in the laws of physics, but is purely mathematical in concept. The theory deals with binary functions that are assumed to have two values representing 1 and 0, and to change instantaneously from one to the other without intermediate values. Also information is assumed to travel instantaneously from the input to the output of the gate.

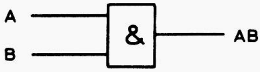
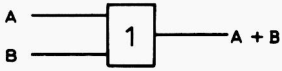
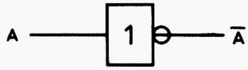
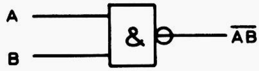
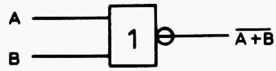
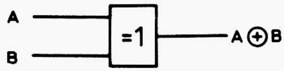
In practice voltages and currents cannot change suddenly, and there are intermediate values during transition, and also internal delays occur in gate circuits. These problems remain in the province of circuit theory whereas switching theory deals with the relations between the binary functions at the input and output of logic networks.

Some of the basic gate elements used in logic design are listed in Table 2.1 with the Boolean algebra expressions and diagrammatic symbols.

The NAND and NOR elements are of particular interest since they are now more widely used—particularly the NAND element—than others in modern computer logic. Logically these are important because they are universal elements, since all other functions can be realised from either. It is thus possible to build the logic of a computer from NAND or NOR elements only. An added reason is that they can be realised with the simplest electronic circuits.

The examples have been shown for two inputs, but in practice gates are made with many inputs. The limitation on the number of inputs is

Table 2.1

Descriptive Term	*Boolean Symbol*	*Diagram Symbol*
AND	$A{\cdot}B$, (AB)	
OR (inclusive OR)	$A+B$	
NOT (inverter)	$\overline{A}$	
NAND (NOT AND)	$\overline{AB}$	
NOR (NOT OR)	$\overline{A+B}$	
exclusive OR	$A \oplus B = A\overline{B}+\overline{A}B$	

due to circuit design considerations, and the convenient number of pins which can be placed on an integrated circuit package.

The diagrammatic symbols used throughout this book are those now in general use, though certain computer companies and countries have standards of their own (see Appendix). Similarly the symbols for Boolean operations are those generally used by computer designers although mathematicians often have a different notation.

Switching Algebra (Boolean Algebra)

The mathematics used in the design and minimisation of logic circuits is called Switching Algebra or Boolean Algebra, and the basic postulates are as follows:

$$\overline{0} = 1$$
$$\overline{1} = 0$$
$$0 + 0 = 0$$
$$0 + 1 = 1$$
$$1 + 0 = 1$$
$$1 + 1 = 1$$
$$0{\cdot}0 = 0$$
$$1{\cdot}0 = 0$$
$$0{\cdot}1 = 0$$
$$1{\cdot}1 = 1$$