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Brigham Young University

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Preface

Microprocessor-Based System Design is directed toward noncomputing applications of the microprocessor. While it is true that many of the principles considered here apply to computing applications, traditional computing topics such as file memory systems, parallel processing, and multiprocessing are not covered. The primary goal of the text is to teach an individual how to design a microprocessor-based electronic system by treating the microprocessor as a component of the overall system.

In order to demonstrate principles or actual systems, a specific microprocessor must be used. Two very different devices are utilized for this purpose throughout the text. The Intel 8051, a very popular microcontroller for control and instrumentation applications, is included in several examples. The architecture of the 8051 is oriented toward these noncomputing applications. The second microprocessor discussed is the Intel 8086. This device represents the opposite extreme in architecture. It is oriented toward computing applications and has been popular for several years in computer systems. The 8086 and the closely related 8088, 80186, and 80286 are used in almost all IBM and IBM-compatible microcomputers. While the emphasis of the text is on noncomputing applications, the coverage of the 8086 will give the reader a more thorough understanding of several aspects of microcomputer systems. It is hoped that a consideration of these two extreme architectures will help the reader adapt easily to other systems that will be encountered in practice.

The title of the book suggests that it is design oriented. Chapter 6, in particular, approaches digital systems from a design rather than an analysis viewpoint. Much of the analysis material of earlier chapters is tied together by the design procedures and examples of Chapter 6.

Ideally, the reader will have completed a first course in digital circuits prior to reading this book. If this is the case, Chapter 1 can be eliminated. This chapter is included to provide background for those who have not had a digital circuits course.

I wish to thank the reviewers of the manuscript for the many constructive suggestions on this effort. It is a pleasure to work with Deborah Moore, editor of the Electrical and Computer Engineering Series, on such a project. Her suggestions, direction, and timely reviews contributed greatly to the improvement of the text. I am also grateful to my students who have suffered through the development of this material. John Ott, in particular, has been very helpful indeed. I appreciate the excellent atmosphere and support provided by Brigham Young University for carrying out this work.

A project such as this is made much more enjoyable by the support of my family. I wish to express gratitude to my daughters, Gail and Shauna, and to my wife, Barbara, for typing the manuscript.

David J. Comer
Provo, Utah

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Introduction

INT.1 PURPOSE OF THE BOOK

During the initial development of the microprocessor (μP) in the early 1970s, it was used primarily in electronic systems. Instruments such as digital voltmeters and high-quality oscilloscopes began to include data manipulation and storage capabilities along with the sophisticated automatic control functions that were previously unavailable. As the quality and performance of μPs improved, they acquired other applications. The most notable area to which the μP was extended was that of computers. Early 8-bit μPs were used for low-precision hobby and business computers. Newer 8-bit and 16-bit devices now form the basis for capable computers. At the present time, computers based on the μP are important to several different fields.

The original use of the μP as a component in a digital system has remained one of its major applications, particularly in electrical engineering. The purpose of this book is to develop principles important to the design of μP-based digital systems. But in order to discuss principles of design, we must first define what a μP is, explain how it operates, and consider how to program it. Because the μP is a sophisticated electronic device, several chapters will be required for these preliminary considerations. Although this text is directed mainly toward noncomputing applications of the μP, the principles discussed will also apply to computing systems.

The Introduction will consider pertinent definitions and some history of the electronics field. Chapter 1 deals with number systems and the simple circuits often used in μP systems. Chapter 2 introduces a general μP and discusses semiconductor memories. Chapter 3 considers two different types of actual μPs. The Intel 8051 is an 8-bit device used almost exclusively in noncomputing applications such as instrumentation or control. The Intel 8086 is a 16-bit μP designed principally for use in computer systems. Both devices are treated in detail in Chapter 3. Programming a μP is the topic of Chapter 4. Chapter 5 discusses exchanging information between digital components and the μP. The final chapter pulls together the principles discussed earlier in order to treat the design of μP-based systems.

All discussion of design emphasizes an orderly, top-down approach in solving the design problems. One aspect of design relates to the area overlapped by the μP controller and the conventional state machine controller. A criterion for choosing between a digital state machine and the μP is suggested.

INT.2 DEFINITIONS

Before we begin a study of the μP we must define the terms *computer, minicomputer, microcomputer,* and *microprocessor.*

A. The Digital Computer

The computer is a collection of electronic circuits and mechanical devices designed to

1. Accept and store instructions and data.
2. Manipulate data as directed by the instructions to produce and store results.
3. Present output information as specified by the instructions.

The digital computer consists of five sections: the *control* unit, the *arithmetic* unit, the *memory*, the *input* unit, and the *output* unit, as shown in Figure I.1.

The input unit can be one of several devices: an input/output typewriter, a keyboard, a card reader, a paper-tape reader, or an analog-to-digital converter. This device converts the signals generated to appropriately coded electrical signals. A keyboard requires conversion from the key's mechanical movement to a corresponding digital code that can be recognized by the computer. Card or paper-tape readers sense hole positions on the card or tape and convert this information into the required code. For digital process control, the raw input signal may be the analog voltage of a measure-

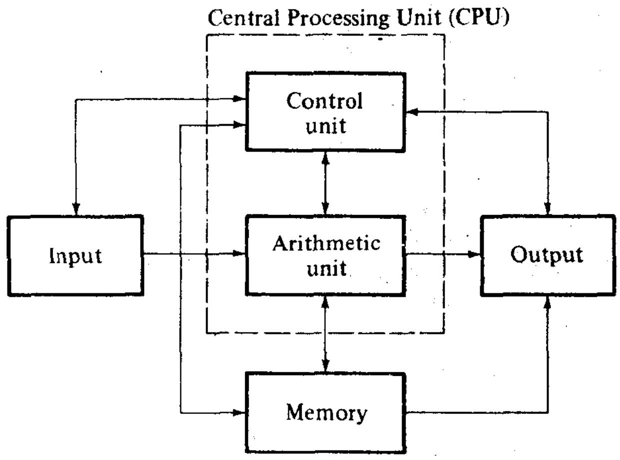

Figure I.1 Block diagram of a computer.

ment circuit. This signal, which might represent the present position of some mechanical apparatus, is then converted to digital form for use by the computer. It is possible for a computer to have more than one input device.

There are also several output devices that can be used, among which are the input/output typewriter, various types of character printers, a card punch, a paper-tape punch, a cathode-ray tube (CRT) terminal, a digital-to-analog converter, and a line printer. The output unit accepts the digital code from the computer and converts it to the proper form of output information. Several output devices may be driven by a single computer.

Every computer has a main memory that stores binary information. The main memory was constructed in the 1960s and 1970s from small magnetic cores. Recently, the semiconductor memory has displaced the magnetic core as the most popular device from which to construct both small and large memories. This section of the computer is quite fast but comparatively expensive for each bit of storage capacity. A very large system may contain room for a few million bytes. A byte consists of eight binary bits, and a medium-sized system may store a million bytes.

In many computer installations, it is necessary to store several millions or even billions of bits for long periods of time. In such instances, semiconductor or core storage is prohibitively expensive and thus slower, less expensive storage is used. This is called *file memory* and may consist of magnetic disks, magnetic tape, or magnetic drums.

The arithmetic unit consists of circuitry for performing addition and other arithmetic and logic operations. The arithmetic unit, memory, input, and output devices operate under the direction of the control unit, which receives instructions from a stored program and directs all other units to carry out these instructions. The arithmetic unit and the control unit together make up the computer's *central processing unit,* or CPU.

The definitions discussed in the preceding paragraphs also apply to large computers, small computers, minicomputers, and microcomputers. Thus, we shall next consider the characteristics of a system that allow it to be classified into various categories. Unfortunately, as technology changes, the defining characteristics also tend to change, resulting in an overlapping of categories, and so we need to compare the original with the present definitions to understand these changes.

As an example of the change in definitions, in the early 1960s the IBM 7090 was considered to be a large computer. Computer size at that time was generally considered to be a function of main memory size. The 64-kbyte memory led to the classification of the 7090 as a large system. In the intervening years, the field has changed so greatly that an Apple II microcomputer can contain 64 kbytes of main memory, but this is now considered one of the smaller systems available. In 1982 Amdahl introduced the 580, which contains up to 32 Mbytes of main memory and can be called a large computer.

B. The Minicomputer

Minicomputers were introduced in the late 1960s. The name implies that these systems are smaller than other computers but does not indicate how the size differs. When first introduced, the minicomputer was smaller than other digital computers in

1. physical size.
2. word size.
3. cost.
4. main memory capacity.

The first minicomputer was introduced in 1965 by the Digital Equipment Corporation. This system, the PDP-8, used a 12-bit word size and sold for about $15,000. A 16-bit system appeared within a few years, offering most of the features of a large computer within the limitations imposed by a small word size. With a smaller word size, less main memory could be accessed directly, leading to smaller memory size. The architecture of the minicomputer was rather simple, requiring fewer components for the CPU. A third factor leading to small size and lower cost was the use of medium-scale integrated circuits. The first minis were easily distinguishable from the larger computers then in use.

Within a few years, however, the boundaries between the two types of computer grew closer and eventually overlapped. The improvement of integrated circuit technology, leading to large-scale integration, resulted in an overall reduction in the size and cost of very large computer systems. Simultaneously, the minicomputer introduced more features at little or no increased cost. Thus, the 32-bit minicomputer became available with a larger main memory and a more complex CPU. At this point, the definition of a minicomputer blurs, as its word size, performance, and memory size have become comparable to those of many existing computers. The 32-bit mini is sometimes referred to as a *midicomputer*.

From this discussion, we can see that arriving at a concise definition of a minicomputer is not an easy task. At least one textbook handles the dilemma by saying that a minicomputer is any computer that the manufacturer calls a minicomputer. We offer the following broad definition:

> A minicomputer is a computer with a word size ranging from 8 to 32 bits that effectively uses integrated circuits to make the system physically small and relatively inexpensive. To distinguish the mini from the microcomputer, the CPU must not be implemented on a single chip.

We shall say more about this definition after we discuss microcomputers.

C. The Microcomputer

In 1971, Intel introduced the 4004 microprocessor (μP). This device was a 4-bit CPU; that is, the control unit and arithmetic unit were implemented on a single chip. According to the criterion stated in the preceding section, the term μP was appropriate. This device was physically small, used a small word size, was inexpensive, and could directly address only a limited amount of memory.

To expand the μP into a microcomputer required the addition of memory and I/O devices. The earlier microcomputers were obviously not designed to compete with the large general-purpose computer or even a larger minicomputer. Very accurate high-speed calculations are simply not possible with the 4-bit microcomputer. The major applications for this device consisted of those requiring a few imprecise calculations based on the status of certain external signals and/or the generation of output control signals.

In 1972, the 8-bit Intel 8008 became available, and other firms were gearing up to produce μPs. One of the early application areas was instrumentation. Adding a μP and memory to an instrument creates the so-called smart instrument. The device can now calculate, make decisions, and store results. A voltmeter may use a μP to automatically change scale range, self-calibrate the instrument, and control the printing of the output voltage at certain time or voltage intervals.

Process control, in which control signals are generated based on the presence or magnitude of certain input signals, is another area of the μP's applications.

As time passed, larger μPs were developed. The 8-bit device became popular, and then the 16-bit μP was introduced. Finally, in the early 1980s a 32-bit device became available. Not only was the bit size increased; so also was the device's performance and the number of components included on the single chip. Some μPs added limited RAM and ROM on the same chip that included the CPU. Thus, the device became something more than a microcircuit CPU. Again we see the familiar problem of definition arising. As the bit size became larger, more memory could be directly accessed and more accurate calculations could be made.

The 8-bit microcomputer made available home and business computers with enough accuracy for typical business applications. Businesses that had purchased $100,000 minis found that $20,000 micros could do the required jobs. Hobbyists found a $500 to $2000 system capable of providing a rather powerful computer facility in the home.

Although there was competition between micros and minis in business applications, the 8-bit micro could not compete as a scientific computer. The introduction of the 16- and 32-bit μPs, however, allowed capable scientific or general-purpose systems to be constructed from these devices. Multiprocessing systems, consisting of several interconnected μPs, provided powerful computer facilities at a lower cost than did equivalent facilities constructed from larger computers. But a disadvantage of this multiprocessor approach is the complexity of its design. It is obviously more difficult to efficiently allocate tasks or work to each processor than to employ a single larger computer. The general areas of effectively interconnecting μPs has been and will continue to be a fruitful area of research and development.

There is a significant physical difference between μPs and other computers that imposes constraints on the overall computer system. This difference stems from the fact that IC chips have physical limits on the number of pins connecting the chip to the outside world. The popular 8-bit configuration used a 40-pin chip, but a minicomputer might use twice this number of connections from the CPU to the memory and peripheral devices. To perform all the functions required, the CPU may require more than 40 connecting paths. Thus, the μP often multiplexes the pins, using a given set of pins for two different functions at two different times. During one time, a particular set of data or information appears on a group of pins, followed by the appearance of a different data set on the same pins at a later time. This multiplexing of pins has led to the need for special external circuits to separate and store the information from the μP until it can be used.

At this point we offer the following definition of the microcomputer:

> A microcomputer is a low-cost computer system that utilizes a single IC chip containing the entire CPU and perhaps some memory. This chip is called a μP. The word size of the microcomputer ranges from 4 to 32 bits.

Although a microcomputer's word size may equal that of a minicomputer, the two are distinguishable by the presence of the μP. Generally, a microcomputer is much less expensive than a comparable minicomputer.

INT.3 HISTORY

There are few other fields that change as drastically and quickly as does the electronics field. New technological developments improve capability and open up new areas that can be serviced by electronics. The next few paragraphs will briefly review some of the significant events in the development of the digital computer.

In the history of science, few events can be considered as significant as the development of the vacuum tube. This single element ushered in the era of electronics and was indispensable to the tremendous growth of the field from the 1920s until the 1960s. The vacuum tube led to the development of radio and television, radar, oscilloscopes, electronic test equipment, and other significant electronic devices.

One area to which the vacuum tube was applied with only limited success, however, was that of the electronic computer. Mechanical calculators and even program-controlled devices date back to the time of Pascal (1600s) and Babbage (early 1800s). In the late 1930s the construction of a large-scale calculator using mechanical and electromechanical devices began. The device was completed in 1943 at IBM under the