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To my daughters Linda and Lisa—
their self-reliance and helpfulness made
this effort possible.

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Chapter 1

The Microprocessor: A Brief Introduction

1.1 The Robots Are Coming...

We cannot predict how much the microprocessor will change our lives, but we can be sure that the changes will be nothing less than revolutionary. The microprocessor brings us one step closer to the universal robot—a machine that looks and acts like a human being. Such a machine will perform difficult, routine, and tedious labor for us. To do this the machine must be able to duplicate all forms of human motion. It must have sensors to detect what is happening around it. It must be able to communicate with its human masters, and above all, it must be able to think, learn, remember, and make decisions. In short, it must have a brain.

Developing an artificial brain suitable for controlling the useful activities of a robot has long been a dream of science fiction writers. Machines that duplicate human motion are as old as the machine age. But machines that think, remember, learn, and make decisions, even to a limited extent, are new.

The relay and vacuum tube computers developed during the 1950s had the necessary brain power, but they were many times too large to fit into the head of a robot. The million-dollar price tag of the computer of that day certainly made their use in every home unthinkable. Even the cost of electricity for the operation of such a brain would have been too much for the average household. Today, however, that same brain power can be provided by a set of integrated circuits small enough to hold in the palm of one hand. Furthermore, these circuits can be produced for less than a hundred dollars, and the power required for their operation is no more than is needed to operate a simple flashlight. The artificial brain is no longer unattainable—it is here!

1.2 Microprocessor Versus Medium-Scale Integrated Circuits (MSI)

Although the microprocessor seems to bring forth a new generation in electronics, it does not provide any new functions. The functions to which microprocessors are presently applied have for many years been available to us through the use of small computers or the same functions have been possible by the assembly of small- and medium-scale integrated logic circuits. However, the microprocessor provides a new approach which, for most applications, proves to have several advantages over older techniques. The advantages may be in flexibility, smaller size, standardization, lower cost, or expandability.

The microprocessor and its peripheral building blocks represent a third generation in digital integrated circuits. Small-scale integrated logic circuits, the first generation of integrated circuit logic building blocks, became available in production quantities as early as 1964. These provided several logic gates* per integrated circuit and more complex logic functions were fabricated by the interconnection of these small-scale devices on circuit boards. By 1970 a second generation of building blocks became available in the form of medium-scale integrated circuits (MSI). The logic functions that are available in MSI form are quite numerous, but each can be classified as one of the following:

- adders
- counters
- registers
- latches
- encoders
- decoders
- multiplexers
- comparators.

When this list is compared with the hardware and software functions available from a microprocessor system, the flexible nature of the microprocessor becomes apparent: It has an arithmetic logic unit and it can add or subtract. The registers in it can be incremented and decremented like a counter. Numbers in its registers can be shifted left or right to provide all register functions. Data can be latched in registers or RAM. The parallel logical instructions can be used to provide all forms of coding and decoding. Data can be multiplexed or demultiplexed at its I/O ports. Although the microprocessor is capable of providing all these

*In this introductory chapter, the reader will encounter some terms that might be unfamiliar. These terms will be defined in the proper context, in later chapters.

functions, it does not perform them simultaneously. It performs such operations one at a time and must be instructed on the order in which they are to be executed, on what data it is to operate, and where to store the results. The microprocessor receives its instructions from a program stored in the program memory. Herein lies its shortcoming. The MSI circuit provides an output within a short propagation delay after the proper inputs arrive. The microprocessor, on the other hand, in doing the same function must fetch and decode one or more instructions, read the data, perform the operation, and move the results out of the way so that the next operation can be executed. All of this takes much more time than is required by the MSI circuit. Although the microprocessor system may have the means to supply any needed logic function, it may not be fast enough for some and it may not be economical enough for others. A digital system that would require only about 20 SSI/MSI circuits may be too small to warrant implementing it with a microprocessor system. (The number 20 is based on today's cost of a minimum microprocessor system of three or four LSI circuits.) In the near future, microcontrollers that contain microprocessor, ROM, RAM, and I/O interface in a single circuit may have a hardware cost cheaper than 20 SSI/MSI circuits.

Hardware cost alone is not sufficient for comparing the relative merits of a microprocessor and selecting it over standard digital logic. Software is more often a determining factor. For the hobbyist, the time spent working on software may be part of the fun, but to the manufacturer, the labor cost for writing, assembling, and debugging programs can be staggering. Also, cost for software is difficult to estimate accurately. However, software is an initial fixed cost and once the program has been perfected that cost can be divided by the number of systems that are produced.

1.3 Types of Microprocessors

There are millions of microprocessors manufactured each year. They come from several dozen integrated circuit manufacturers who make a multitude of variations. Most are of MOS technology, but a few are CMOS, and recently TTL and I^2L devices have been added to the list. They vary in size of both address and data bus, in size of instruction set, and in number of registers. Most are processing units which must be used with external memory, but some are microcontrollers, containing CPU, ROM, RAM, and I/O ports on a single chip. The typical microprocessor is a 40-pin dual-in-line integrated circuit as Figure 1.1(a) shows. The 40-pin circuit in itself seems small considering the many remarkable functions it can perform. Yet the actual active element within the 40-pin circuit as seen by the circuit with the lid removed is a chip of silicon only .160″ × .160″ in size. This chip of silicon contains arrays of minute transistors precisely connected to produce all of the needed logic functions. Figure 1.2 shows a photograph of the chip of the 8080A microprocessor. Of the many microprocessors produced each year, a

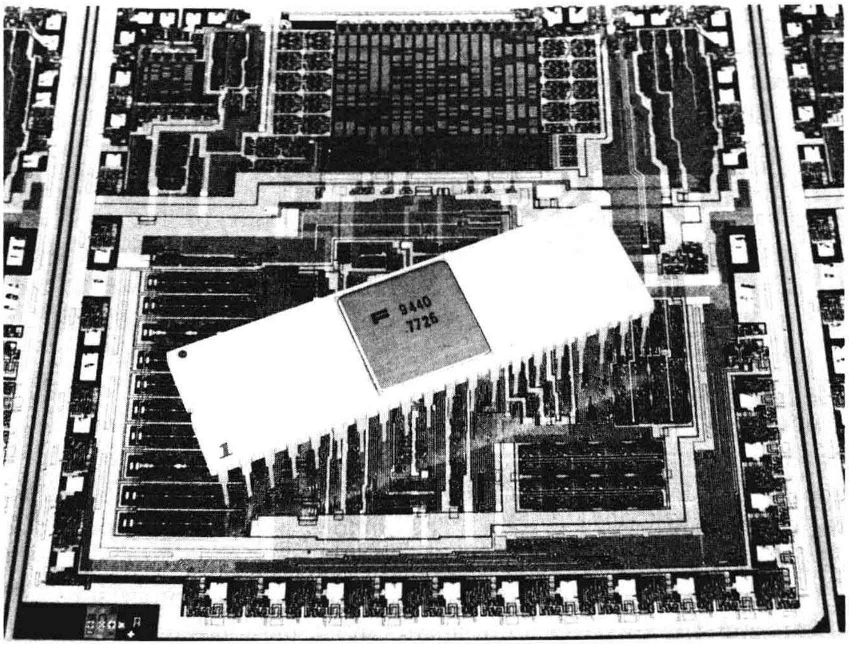
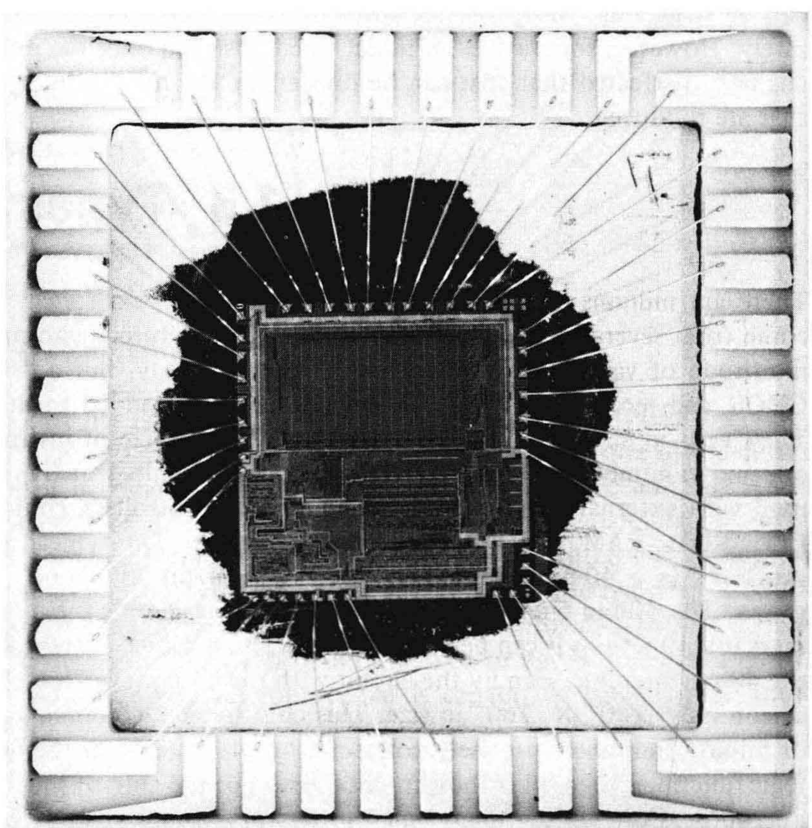


FIGURE 1.1 (a) The 9440 Microflame CPU, a 16-bit bipolar microprocessor. The 40-pin package is 2 inches long and 0.6 inches wide. The die photograph, shown as background, is magnified 30 times.



(b) Similar microprocessor unit with metal lid removed showing bond wire connections between the die and the 40-pin package. (*Courtesy of Fairchild Camera & Instrument Corp.*)

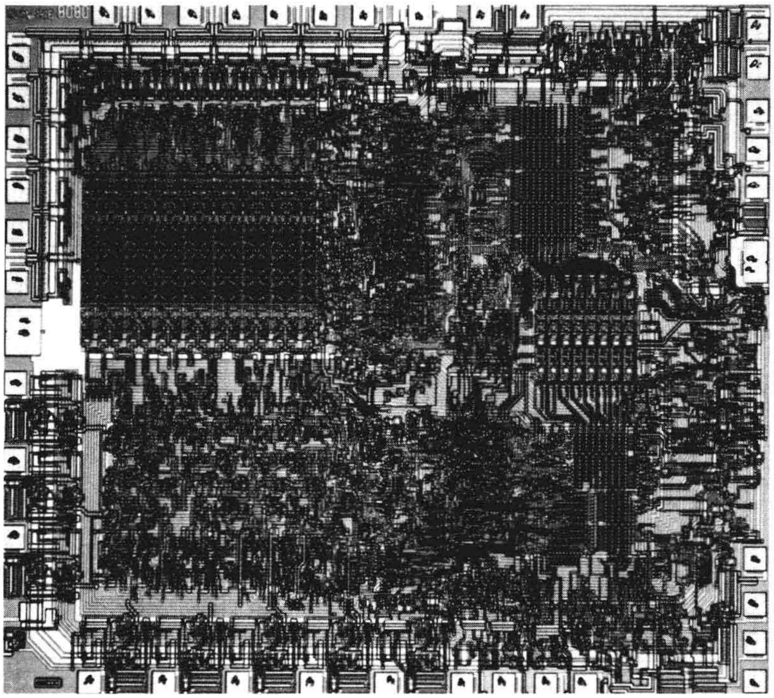


FIGURE 1.2 Silicon chip (die) of the 8085 Microprocessor. (*Courtesy of Intel Corp.*)

substantial number are assembled into calculators and similar devices. Of primary concern to us, however, are those sold to private users or equipment manufacturers as integrated circuits. Table 1.1 lists some widely used microprocessors, their characteristics, and their sources.

Table 1.2 lists the microcontrollers which differ from microprocessors in that they contain internal RAM, ROM, or I/O ports and are often considered single chip microcomputers. The amount of onboard RAM or ROM is usually small, but it is enough to allow these devices to perform dedicated functions which require only short programs such as the control of household appliances.

At the other end of the scale are the microprocessor building blocks such as the 1-bit and 4-bit slice devices listed in Table 1.3. The heart of a microprocessor is the arithmetic logic unit (ALU). This unit combined with an accumulator is involved in all instructions performed by a microprocessor other than the move, store, and transfer instructions. A 1-bit microprocessor slice is essentially a 1-bit arithmetic logic unit. Microprocessor slices can be paralleled to develop a microprocessor of any needed data-bit size. Five 4-bit slices can be paralleled to develop a microprocessor of 20 data bits. As the list of 2900 devices in Table 1.3 shows, numerous other circuits are required to provide functions other than ALU. Developing microprocessors from these building blocks is not a task for beginners. It is more difficult than employing a standard design device. These circuits however are TTL and can provide systems with limited instructions but of much higher speed than is available from standard devices.

TABLE 1.1 Microprocessor characteristics and manufacturers.

MODEL	DATA BITS	ADDRESS BITS	TECHNOLOGY	POWER SUPPLIES	PINS PER CKT	ORIGINATOR	OTHER SOURCES	REMARKS
4040	4	6	PMOS	-15V	24	INTEL		
PPS-4	4		PMOS	-17V	42	ROCKWELL		
F-8	8	16	NMOS	+12 +5	40	FAIRCHILD	MOSTEK	
8080A	8	16	NMOS	+5V -5V +12V	40	INTEL	AMD NATIONAL T.I. NEC	
8085	8*	16*	NMOS	+5V	40	INTEL	AMD	
6800	8	16	NMOS	+5V	40	MOTOROLA	FAIRCHILD AMI	
650X	8	16	NMOS	+5V	40	MOS TECHNOLOGY	SYNERTEK ROCKWELL	
SC/MP	8*	16*	NMOS	-12V or +5 -7	40	NATIONAL		4 AD/DATA USE +5V -7V FOR TTL COMPOUT
Z80	8	16	NMOS	+5V	40	ZILOG	MOSTEK	
1802	8	16	CMOS	+10V	40	RCA	SOLID STATE SCIENTIFIC	
2650	8	15	NMOS	+5V	40	SIGNETICS		
6100	12	12	CMOS	+5V or +10V	40	INTERSIL	HARRIS	EMULATES PDP-8
8086	16*	20*	NMOS	+5V	40	INTEL	MOSTEK	
1600	16*	16*	NMOS	+5V +12V -3V	40	GENERAL INSTRUMENT		PDP-II TYPE INSTRUCTIONS
PACE	16*	16*	NMOS	+5V -12V +3V	40	NATIONAL		
9440	16*	15	BIPOLAR	+5V	40	FAIRCHILD		(MICROFLAME^{TM})
TMS 9900	16	15	NMOS	+5V -5V +12V	64	TEXAS INSTRUMENT	AMI	AVAILABLE IN I^2L
68000	16	23	NMOS	+12V	64	MOTOROLA		

*Multiplexed address and data.

TABLE 1.2 Microcontrollers. (Sometimes called single chip microcomputers.)

NUMBER (MFG.)	INTERNAL			EXTERNAL BUS EXPANSION	OTHER FEATURES
	RAM	ROM	I/O		
8048 (INTEL)	64 × 8	1K × 8	27 LINES 3 8-BIT PORTS +3	1 8-BIT PORT USED AS HIGH ADDRESS BYTE 1 8-BIT PORT USED AS MULTIPLEXED ADDRESS LOW BYTE WITH DATA BYTE	ON BOARD CLOCK TIMER/COUNTER
6801E (MOTOROLA)	128 × 8	2K × 8	33 LINES + SERIAL	8-BIT DATA (PORT3) 8-BIT ADR (PORT4) OR 8-BIT DATA } PORT3 8-BIT ADRL } MUX. 8-BIT ADRH (PORT4)	ON BOARD CLOCK TIMER/COUNTER
6500/1 (MOS TECHNOLOGY) (ROCKWELL)	64 × 8	2K × 8	32 LINES (4 PORTS)		ON BOARD CLOCK TIMER/COUNTER FIVE INTERRUPTS
3870 (MOSTEK) (FAIRCHILD)	64 × 8	2K × 8	32 LINES (4 PORTS)		ON BOARD CLOCK TIMER/COUNTER EXTERNAL INTERRUPT

TABLE 1.3 2900 4-bit slice Microprocessor series. These circuits are high speed building blocks which can be assembled to provide microprocessors of varied size.

CIRCUIT NUMBER	NAME	CONTENT-DESCRIPTION	PIN NO.
2901	4-BIT BIPOLAR MICROPROCESSOR SLICE	4-BIT ARITHMETIC LOGIC UNIT STATUS FLAGS WORKING REGISTERS	40
2902	HIGH-SPEED CARRY LOOK-AHEAD	SPEED UP ARITHMETIC BY ANTICIPATING CARRY IN ADVANCE	16
2909	MICROPROGRAM SEQUENCER	CONTROLS ADDRESSING WITHIN A 2900 SYSTEM	28
2911			20
2913	PRIORITY INTERRUPT EXPANDER	EXPANDS 2914	20
2914	VECTORED PRIORITY INTERRUPT ENCODER	CONTROL 2900 MICROPROCESSOR VECTORED INTERRUPT SYSTEM	40
2905	QUAD BUS TRANSCEIVERS	OPEN COLLECTOR	24
2906		OPEN COLLECTOR WITH PARITY	24
2907		3-STATE WITH PARITY	20
2915		3-STATE W/INTERFACE LOGIC	24
2916		" " PLUS PARITY	24
2917		" " "	20
2918	QUAD D REGISTER	3-STATE OUTPUTS	16
29700	64-BIT RAM	NONINVERTING	16
29702		INVERTING	
29704	16-WORD BY 4-BIT RAM	2-PORT RAM	28
29750	PROM	32-WORD BY 8-BIT	16
29760		256-WORD BY 4-BIT	16
29790	FPLA	FIELD PROGRAMMABLE LOGIC ARRAY	28

1.4 Hardware Development

Enhancing the growth of microprocessor applications has been a parallel development of larger and better memory circuits for use with microprocessors. Fusible link programmable read only memories have advanced from as few as 256 bits per circuit in 1973 to as many as 8192 bits per circuit in 1978. Equally important has been the development of static RAMS of higher density, from 1024 bits per circuit in 1973 to the 8192 bits per circuit available in 1979. Growing even more rapidly than the memory circuits is the development of special peripheral devices designed to facilitate numerous microprocessor applications. A list of these and their functions is given in Table 1.4.

TABLE 1.4 Microprocessor Peripheral Circuits
The circuits listed are designed to facilitate microprocessor control of numerous peripheral devices.

CIRCUIT NUMBER	DESCRIPTION	MFG.	PINS
6821	PERIPHERAL INTERFACE ADAPTER	MOTOROLA	40
8255		INTEL	40
6840	PROGRAMMABLE TIMER	MOTOROLA	24
8253		INTEL	24
6843	FLOPPY DISK CONTROLLER	MOTOROLA	40
8271		INTEL	40
6844	DIRECT MEMORY ACCESS	MOTOROLA	40
8257	CONTROLLER	INTEL	40
6845	CRT CONTROLLER	MOTOROLA	40
8275		INTEL	40
6850	COMMUNICATIONS INTERFACE	MOTOROLA	24
8251		INTEL	28
6828	PRIORITY INTERRUPT CONTROLLER	MOTOROLA	24
8259		INTEL	28
8279	PROGRAMMABLE KEYBOARD/ DISPLAY CONTROLLER	INTEL	40

1.5 Software Development Tools

Short, dedicated microprocessor programs are relatively easy to write and are seldom difficult to debug, but an 8-bit microprocessor with 16-bit address bus may be used in a system having thousands of instructions. Figure 1.3 shows a Micro Control Co. memory tester designed to provide both production and development test of memory and other LSI circuits. It is controlled by a single 8080A microprocessor. It communicates with the operator through either a teletype or a CRT terminal. A minimum system uses 16,000 bytes of memory and communicates with 200 I/O ports within the system. A microprocessor system of this magnitude requires a program of such length that a computer program is needed to assist in assembling and editing it. Figure 1.4 shows a development system for the Intel 8080/8085 microprocessor. Large

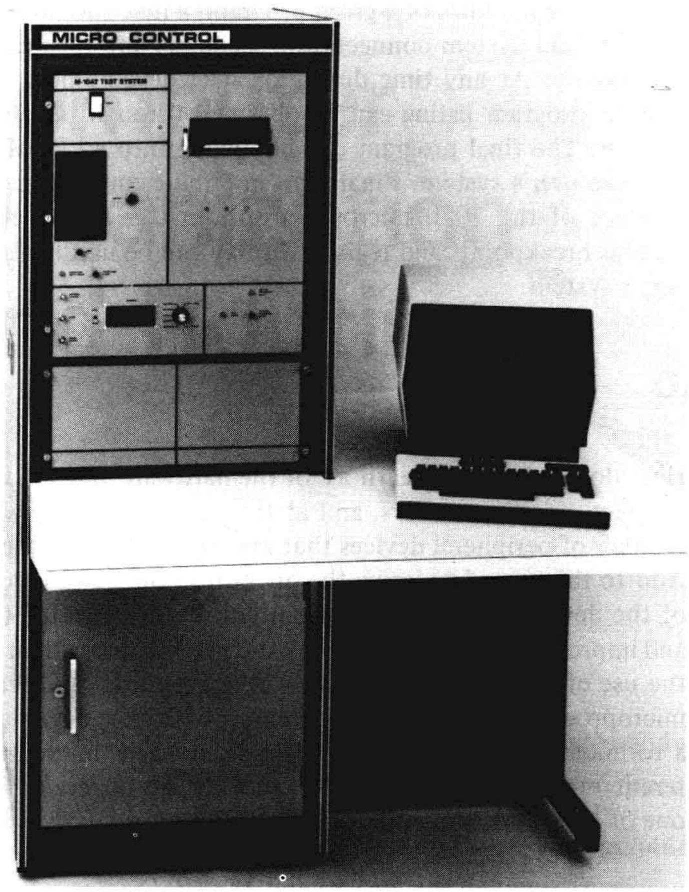
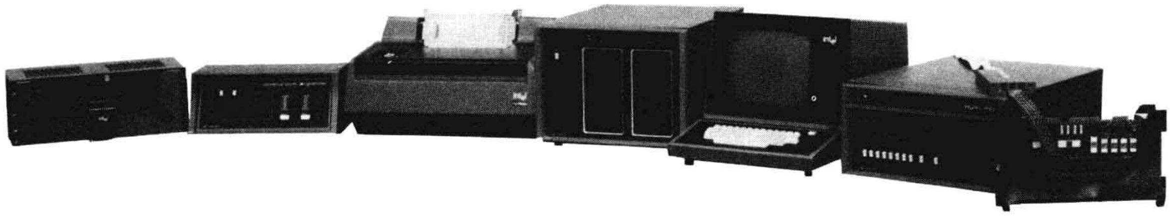


FIGURE 1.3 Memory Tester Microprocessor Controlled. (*Courtesy of Micro Control Co.*)

programs are generally developed in modules of small routines and segments. These are entered on the CRT terminal of a development system and edited. An editor program within the system recognizes certain types of errors, computes conditional jumps, and provides for the insertion of missing instructions. After each program module is edited it is assembled. The assembler converts the alphabetical mnemonic code used by the programmer into the machine code used by the microprocessor. It assigns consecutive addresses to each instruction. Upon completion of assembly, the program segments can be stored in a library on floppy disk. Programs or segments of software can be debugged by execution of the program in a simulated system, stopping the program at critical points (breakpoints) to allow the examination of data in microprocessor registers and key memory locations. On completion of all

FIGURE 1.4 The Intellec® Development System.
From left to right: High Speed Paper Tape Reader, Universal PROM Programmer, Printer, Floppy Dukette Operating System, CRT Terminal and Keyboard, In-Circuit Emulator. (*Courtesy of Intel Corp.*)



segments or modules of a given program, a link and locate feature in the development system connects the segments and locates them correctly in memory. At any time during or after development of a program, a printed program listing can be obtained through the RS232C teletype adapter. The final program can be loaded into a PROM for installation into the user's system. Finally an in circuit emulator can be connected in place of the 8080 microprocessor. In this way the debug routines such as breakpoints and register display can be used to troubleshoot the user's system.

1.6 The Challenge

How does a beginner learn all of the hardware and software features of so many microprocessors, and at the same time cope with the growing number of peripheral devices that are used to enhance their applications? Add to this a need to know the operating commands and characteristics of the development systems. Combine all this with the feeling that new and improved devices are reaching the market faster than one can master the use of older models. Knowing the capabilities and features of all the microprocessors as well as keeping up with new developments presents a formidable learning task. On the other hand, microprocessors of different models are more alike than they are different, and fortunately one of two models are used in nearly 90% of present-day applications.

Figure 1.5 shows an operating model of a traffic light. A microprocessor supplies the timing and the sequencing of the red, yellow, green, and left turn signals. It requires a microprocessor system of only four circuits or as few as two circuits with a microcontroller. It has a program of fewer than 70 instructions. It is not formidable at all. It is quite simple. It works, and there are thousands of applications like it. This is where we begin.

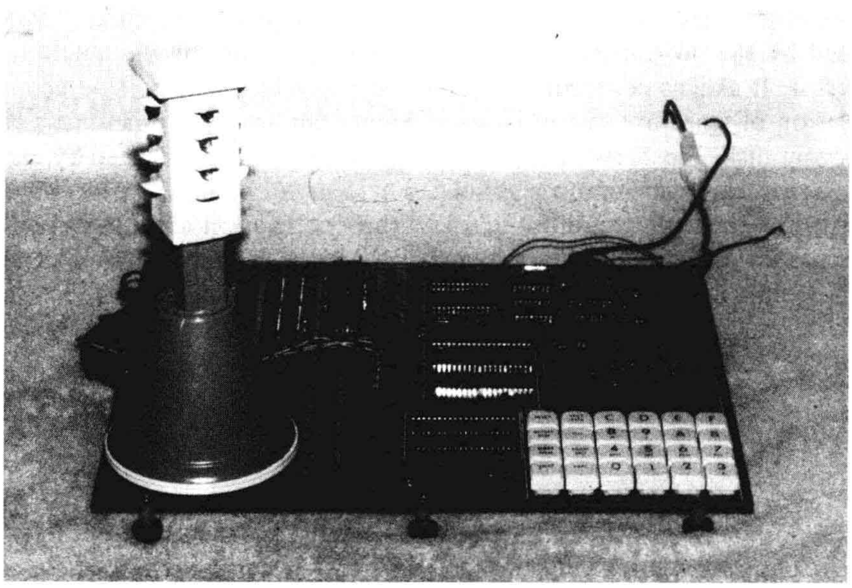


FIGURE 1.5 Traffic light model connected to a microprocessor system.

Chapter 2

Computer Organization and Routines

Objectives

On completion of this chapter you will be able to:

- Identify the numerous functions of a microprocessor and its associated components.
- Use the vocabulary peculiar to microprocessor and computer systems.
- Use the vocabulary associated with microprocessor software.
- Read and assemble a microprocessor program listing.
- Recognize the addressing modes of microprocessor instructions.

2.1 Systems Components

Any computer, regardless of its size, is made up of an input device, a timing and control unit, an arithmetic logic unit, a memory unit, and an output device. See Figure 2.1.

The timing and control circuit combined with the arithmetic unit is called a **central processor** or **central processing unit**, (**CPU**). When these units are provided in a single integrated circuit, that circuit is called a **microprocessor**, (**MPU**). In addition to the arithmetic unit, the processor contains sets of **registers**, counters, and **decoding circuits**. Using these logic circuits, the processor can respond to a variety of simple **instructions**. The list of instructions that a processor can execute is known as an **instruction set**. Processors may have instruction sets with