Logic and Computer Design FUNDAMENTALS

Fifth Edition

M. MORRIS MANO • CHARLES R. KIME • TOM MARTIN

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Preface

The objective of this text is to serve as a cornerstone for the learning of logic design, digital system design, and computer design by a broad audience of readers. This fifth edition marks the continued evolution of the text contents. Beginning as an adaptation of a previous book by the first author in 1997, it continues to offer a unique combination of logic design and computer design principles with a strong hardware emphasis. Over the years, the text has followed industry trends by adding new material such as hardware description languages, removing or de-emphasizing material of declining importance, and revising material to track changes in computer technology and computer-aided design.

New to This Edition

The fifth edition reflects changes in technology and design practice that require computer system designers to work at higher levels of abstraction and manage larger ranges of complexity than they have in the past. The level of abstraction at which logic, digital systems, and computers are designed has moved well beyond the level at which these topics are typically taught. The goal in updating the text is to more effectively bridge the gap between existing pedagogy and practice in the design of computer systems, particularly at the logic level. At the same time, the new edition maintains an organization that should permit instructors to tailor the degree of technology coverage to suit both electrical and computer engineering and computer science audiences. The primary changes to this edition include:

- Chapter 1 has been updated to include a discussion of the layers of abstractions in computing systems and their role in digital design, as well as an overview of the digital design process. Chapter 1 also has new material on alphanumeric codes for internationalization.
- The textbook introduces hardware description languages (HDLs) earlier, starting in Chapter 2. HDL descriptions of circuits are presented alongside logic schematics and state diagrams throughout the chapters on combinational and sequential logic design to indicate the growing importance of HDLs in contemporary digital system design practice. The material on propagation delay, which is a first-order design constraint in digital systems, has been moved into Chapter 2.
- Chapter 3 combines the functional block material from the old Chapter 3 and the arithmetic blocks from the old Chapter 4 to present a set of commonly

occurring combinational logic functional blocks. HDL models of the functional blocks are presented throughout the chapter. Chapter 3 introduces the concept of hierarchical design.

- Sequential circuits appear in Chapter 4, which includes both the description of design processes from the old Chapter 5, and the material on sequential circuit timing, synchronization of inputs, and metastability from the old Chapter 6. The description of JK and T flip-flops has been removed from the textbook and moved to the online Companion Website.
- Chapter 5 describes topics related to the implementation of digital hardware, including design of complementary metal-oxide (CMOS) gates and programmable logic. In addition to much of the material from the old Chapter 6, Chapter 5 now includes a brief discussion of the effect of testing and verification on the cost of a design. Since many courses employing this text have lab exercises based upon field programmable gate arrays (FPGAs), the description of FPGAs has been expanded, using a simple, generic FPGA architecture to explain the basic programmable elements that appear in many commercially available FPGA families.
- The remaining chapters, which cover computer design, have been updated to reflect changes in the state-of-the art since the previous edition appeared. Notable changes include moving the material on high-impedance buffers from the old Chapter 2 to the bus transfer section of Chapter 6 and adding a discussion of how procedure call and return instructions can be used to implement function calls in high level languages in Chapter 9.

Offering integrated coverage of both digital and computer design, this edition of *Logic and Computer Design Fundamentals* features a strong emphasis on fundamentals underlying contemporary design. Understanding of the material is supported by clear explanations and a progressive development of examples ranging from simple combinational applications to a CISC architecture built upon a RISC core. A thorough coverage of traditional topics is combined with attention to computer-aided design, problem formulation, solution verification, and the building of problem-solving skills. Flexibility is provided for selective coverage of logic design, digital system design, and computer design topics, and for coverage of hardware description languages (none, VHDL, or Verilog®).

With these revisions, Chapters 1 through 4 of the book treat logic design, Chapters 5 through 7 deal with digital systems design, and Chapters 8 through 12 focus on computer design. This arrangement provides solid digital system design fundamentals while accomplishing a gradual, bottom-up development of fundamentals for use in top-down computer design in later chapters. Summaries of the topics covered in each chapter follow.

Logic Design

Chapter 1, Digital Systems and Information, introduces digital computers, computer systems abstraction layers, embedded systems, and information representation including number systems, arithmetic, and codes.

Chapter 2, Combinational Logic Circuits, deals with gate circuits and their types and basic ideas for their design and cost optimization. Concepts include Boolean algebra, algebraic and Karnaugh-map optimization, propagation delay, and gate-level hardware description language models using structural and dataflow models in both VHDL and Verilog.

Chapter 3, Combinational Logic Design, begins with an overview of a contemporary logic design process. The details of steps of the design process including problem formulation, logic optimization, technology mapping to NAND and NOR gates, and verification are covered for combinational logic design examples. In addition, the chapter covers the functions and building blocks of combinational design including enabling and input-fixing, decoding, encoding, code conversion, selecting, distributing, addition, subtraction, incrementing, decrementing, filling, extension and shifting, and their implementations. The chapter includes VHDL and Verilog models for many of the logic blocks.

Chapter 4, Sequential Circuits, covers sequential circuit analysis and design. Latches and edge-triggered flip-flops are covered with emphasis on the D type. Emphasis is placed on state machine diagram and state table formulation. A complete design process for sequential circuits including specification, formulation, state assignment, flip-flop input and output equation determination, optimization**,** technology mapping, and verification is developed. A graphical state machine diagram model that represents sequential circuits too complex to model with a conventional state diagram is presented and illustrated by two real world examples. The chapter includes VHDL and Verilog descriptions of a flip-flop and a sequential circuit, introducing procedural behavioral VHDL and Verilog language constructs as well as test benches for verification. The chapter concludes by presenting delay and timing for sequential circuits, as well as synchronization of asynchronous inputs and metastability.

Digital Systems Design

Chapter 5, Digital Hardware Implementation, presents topics focusing on various aspects of underlying technology including the MOS transistor and CMOS circuits, and programmable logic technologies. Programmable logic covers read-only memories, programmable logic arrays, programmable array logic, and field programmable gate arrays (FPGAs). The chapter includes examples using a simple FPGA architecture to illustrate many of the programmable elements that appear in more complex, commercially available FPGA hardware.

Chapter 6, Registers and Register Transfers, covers registers and their applications. Shift register and counter design are based on the combination of flip-flops with functions and implementations introduced in Chapters 3 and 4. Only the ripple counter is introduced as a totally new concept. Register transfers are considered for both parallel and serial designs and time–space trade-offs are discussed. A section focuses on register cell design for multifunction registers that perform multiple operations. A process for the integrated design of datapaths and control units using register transfer statements and state machine diagrams is introduced and illustrated by two real world examples. Verilog and VHDL descriptions of selected register types are introduced.

Chapter 7, Memory Basics, introduces static random access memory (SRAM) and dynamic random access memory (DRAM), and basic memory systems. It also describes briefly various distinct types of DRAMs.

Computer design

Chapter 8, Computer Design Basics, covers register files, function units, datapaths, and two simple computers: a single-cycle computer and a multiple-cycle computer. The focus is on datapath and control unit design formulation concepts applied to implementing specified instructions and instruction sets in single-cycle and multiple-cycle designs.

Chapter 9, Instruction Set Architecture, introduces many facets of instruction set architecture. It deals with address count, addressing modes, architectures, and the types of instructions and presents floating-point number representation and operations. Program control architecture is presented including procedure calls and interrupts.

Chapter 10, RISC and CISC Processors, covers high-performance processor concepts including a pipelined RISC processor and a CISC processor. The CISC processor, by using microcoded hardware added to a modification of the RISC processor, permits execution of the CISC instruction set using the RISC pipeline, an approach used in contemporary CISC processors. Also, sections describe high-performance CPU concepts and architecture innovations including two examples of multiple CPU microprocessors.

Chapter 11, Input–Output and Communication, deals with data transfer between the CPU and memory, input–output interfaces and peripheral devices. Discussions of a keyboard, a Liquid Crystal Display (LCD) screen, and a hard drive as peripherals are included, and a keyboard interface is illustrated. Other topics range from serial communication, including the Universal Serial Bus (USB), to interrupt system implementation.

Chapter 12, Memory Systems, focuses on memory hierarchies. The concept of locality of reference is introduced and illustrated by consideration of the cache/main memory and main memory/hard drive relationships. An overview of cache design parameters is provided. The treatment of memory management focuses on paging and a translation lookaside buffer supporting virtual memory.

In addition to the text itself, a Companion Website and an Instructor's Manual are provided. Companion Website (www.pearsonhighered.com/mano) content includes the following: 1) reading supplements including material deleted from prior editions, 2) VHDL and Verilog source files for all examples, 3) links to computer-aided design tools for FPGA design and HDL simulation, 4) solutions for about one-third of all text chapter problems, 5) errata, 6) PowerPoint® slides for Chapters 1 through 8, 7) projection originals for complex figures and tables from the text, and 8) site news sections for students and instructors pointing out new material, updates, and corrections. Instructors are encouraged to periodically check the instructor's site news so that they are aware of site changes. **Instructor's Manual** content includes suggestions for use of the book and all problem solutions. Online access to this manual is available from Pearson to instructors at academic institutions who adopt the

book for classroom use. The suggestions for use provide important detailed information for navigating the text to fit with various course syllabi.

Because of its broad coverage of both logic and computer design, this book serves several different objectives in sophomore through junior level courses. Chapters 1 through 9 with selected sections omitted, provide an overview of hardware for computer science, computer engineering, electrical engineering, or engineering students in general in a single semester course. Chapters 1 through 4 possibly with selected parts of 5 through 7 give a basic introduction to logic design, which can be completed in a single quarter for electrical and computer engineering students. Covering Chapters 1 through 7 in a semester provides a stronger, more contemporary logic design treatment. The entire book, covered in two quarters, provides the basics of logic and computer design for computer engineering and science students. Coverage of the entire book with appropriate supplementary material or a laboratory component can fill a two-semester sequence in logic design and computer architecture. Due to its moderately paced treatment of a wide range of topics, the book is ideal for self-study by engineers and computer scientists. Finally, all of these various objectives can also benefit from use of reading supplements provided on the Companion Website.

The authors would like to acknowledge the instructors whose input contributed to the previous edition of the text and whose influence is still apparent in the current edition, particularly Professor Bharat Bhuva, Vanderbilt University; Professor Donald Hung, San Jose State University; and Professors Katherine Compton, Mikko Lipasti, Kewal Saluja, and Leon Shohet, and Faculty Associate Michael Morrow, ECE, University of Wisconsin, Madison. We appreciate corrections to the previous editions provided by both instructors and students, most notably, those from Professor Douglas De Boer of Dordt College. In getting ready to prepare to think about getting started to commence planning to begin working on the fifth edition, I received valuable feedback on the fourth edition from Patrick Schaumont and Cameron Patterson at Virginia Tech, and Mark Smith at the Royal Institute of Technology (KTH) in Stockholm, Sweden. I also benefited from many discussions with Kristie Cooper and Jason Thweatt at Virginia Tech about using the fourth edition in the updated version of our department's Introduction to Computer Engineering course. I would also like to express my appreciation to the folks at Pearson for their hard work on this new edition. In particular, I would like to thank Andrew Gilfillan for choosing me to be the new third author and for his help in planning the new edition; Julie Bai for her deft handling of the transition after Andrew moved to another job, and for her guidance, support, and invaluable feedback on the manuscript; Pavithra Jayapaul for her help in text production and her patience in dealing with my delays (especially in writing this preface!); and Scott Disanno and Shylaja Gattupalli for their guidance and care in producing the text. Special thanks go to Morris Mano and Charles Kime for their efforts in writing the previous editions of this book. It is an honor and a privilege to have been chosen as their successor. Finally, I would like to thank Karen, Guthrie, and Eli for their patience and support while I was writing, especially for keeping our mutt Charley away from this laptop so that he didn't eat the keys like he did with its short-lived predecessor.

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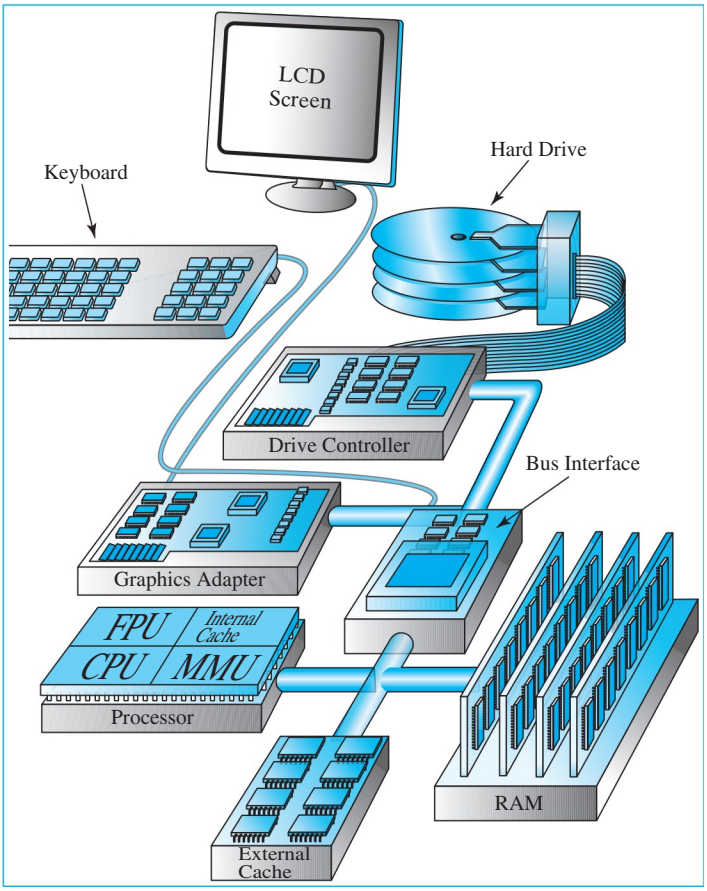
Logic and Computer Design Fundamentals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CHAPTER

1

Digital Systems and Information

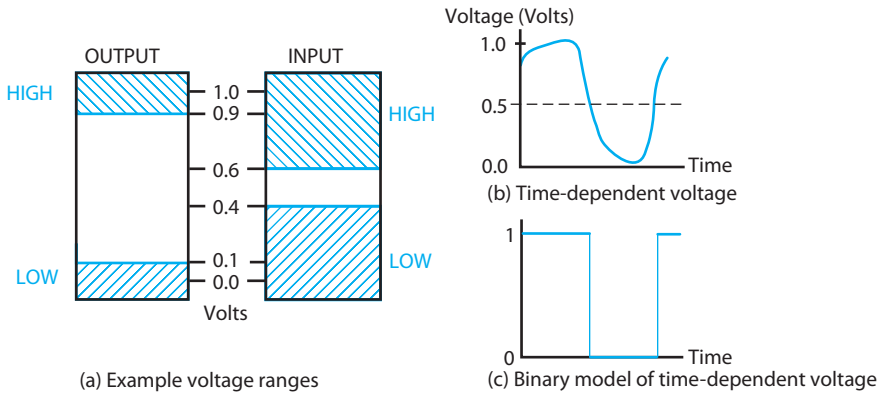
This book deals with logic circuits and digital computers. Early computers were used for computations with discrete numeric elements called *digits* (the Latin word for fingers)—hence the term *digital computer*. The use of "digital" spread from the computer to logic circuits and other systems that use discrete elements of information, giving us the terms *digital circuits* and *digital systems*. The term *logic* is applied to circuits that operate on a set of just two elements with values True (1) and False (0). Since computers are based on logic circuits, they operate on patterns of elements from these two-valued sets, which are used to represent, among other things, the decimal digits. Today, the term "digital circuits" is viewed as synonymous with the term "logic circuits."

The *general-purpose digital computer* is a digital system that can follow a stored sequence of instructions, called a *program*, that operates on data. The user can specify and change the program or the data according to specific needs. As a result of this flexibility, general-purpose digital computers can perform a variety of information-processing tasks, ranging over a very wide spectrum of applications. This makes the digital computer a highly general and very flexible digital system. Also, due to its generality, complexity, and widespread use, the computer provides an ideal vehicle for learning the concepts, methods, and tools of digital system design. To this end, we use the exploded pictorial diagram of a computer of the class commonly referred to as a PC (personal computer) given on the opposite page. We employ this generic computer to highlight the significance of the material covered and its relationship to the overall system. A bit later in this chapter, we will discuss the various major components of the generic computer and see how they relate to a block diagram commonly used to represent a computer. We then describe the concept of layers of abstraction in digital system design, which enables us to manage the complexity of designing and programming computers constructed using billions of transistors. Otherwise, the remainder of the chapter focuses on the digital systems in our daily lives and introduces approaches for representing information in digital circuits and systems.

1-1 Information Representation

Digital systems store, move, and process information. The information represents a broad range of phenomena from the physical and man-made world. The physical world is characterized by parameters such as weight, temperature, pressure, velocity, flow, and sound intensity and frequency. Most physical parameters are *continuous*, typically capable of taking on all possible values over a defined range. In contrast, in the man-made world, parameters can be discrete in nature, such as business records using words, quantities, and currencies, taking on values from an alphabet, the integers, or units of currency, respectively. In general, information systems must be able to represent both continuous and discrete information. Suppose that temperature, which is continuous, is measured by a sensor and converted to an electrical voltage, which is likewise continuous. We refer to such a continuous voltage as an *analog signal*, which is one possible way to represent temperature. But, it is also possible to represent temperature by an electrical voltage that takes on *discrete* values that occupy only a finite number of values over a range, for example, corresponding to integer degrees centigrade between −40 and +119. We refer to such a voltage as a *digital signal*. Alternatively, we can represent the discrete values by multiple voltage signals, each taking on a discrete value. At the extreme, each signal can be viewed as having only two discrete values, with multiple signals representing a large number of discrete values. For example, each of the 160 values just mentioned for temperature can be represented by a particular combination of eight two-valued signals. The signals in most present-day electronic digital systems use just two discrete values and are therefore said to be *binary*. The two discrete values used are often called 0 and 1, the digits for the binary number system.

We typically represent the two discrete values by ranges of voltage values called HIGH and LOW. Output and input voltage ranges are illustrated in Figure 1-1(a). The HIGH output voltage value ranges between 0.9 and 1.1 volts, and the LOW output voltage value between −0.1 and 0.1 volts. The high input range allows 0.6 to 1.1 volts to be recognized as a HIGH, and the low input range allows



(a) Example voltage ranges

(b) Time-dependent voltage

(c) Binary model of time-dependent voltage

□ **FIGURE 1-1**
Examples of Voltage Ranges and Waveforms for Binary Signals

−0.1 to 0.4 volts to be recognized as a LOW. The fact that the input ranges are wider than the output ranges allows the circuits to function correctly in spite of variations in their behavior and undesirable "noise" voltages that may be added to or subtracted from the outputs.

We give the output and input voltage ranges a number of different names. Among these are HIGH (H) and LOW (L), TRUE (T) and FALSE (F), and 1 and 0. It is natural to associate the higher voltage ranges with HIGH or H, and the lower voltage ranges with LOW or L. For TRUE and 1 and FALSE and 0, however, there is a choice. TRUE and 1 can be associated with either the higher or lower voltage range and FALSE and 0 with the other range. Unless otherwise indicated, we assume that TRUE and 1 are associated with the higher of the voltage ranges, H, and the FALSE and 0 are associated with the lower of the voltage ranges, L. This particular convention is called *positive logic*.

It is interesting to note that the values of voltages for a digital circuit in Figure 1-1(a) are still continuous, ranging from −0.1 to +1.1 volts. Thus, the voltage is actually analog! The actual voltages values for the output of a very high-speed digital circuit are plotted versus time in Figure 1-1(b). Such a plot is referred to as a *waveform*. The interpretation of the voltage as binary is based on a model using voltage ranges to represent discrete values 0 and 1 on the inputs and the outputs. The application of such a model, which redefines all voltage above 0.5 V as 1 and below 0.5 V as 0 in Figure 1-1(b), gives the waveform in Figure 1-1(c). The output has now been interpreted as binary, having only discrete values 1 and 0, with the actual voltage values removed. We note that digital circuits, made up of electronic devices called transistors, are designed to cause the outputs to occupy the two distinct output voltage ranges for 1 (H) and 0 (L) in Figure 1-1, whenever the outputs are not changing. In contrast, analog circuits are designed to have their outputs take on continuous values over their range, whether changing or not.

Since 0 and 1 are associated with the binary number system, they are the preferred names for the signal ranges. A binary digit is called a *bit*. Information is represented in digital computers by groups of bits. By using various coding techniques, groups of bits can be made to represent not only binary numbers, but also other groups of discrete symbols. Groups of bits, properly arranged, can even specify to the computer the program instructions to be executed and the data to be processed.

Why is binary used? In contrast to the situation in Figure 1-1, consider a system with 10 values representing the decimal digits. In such a system, the voltages available—say, 0 to 1.0 volts—could be divided into 10 ranges, each of length 0.1 volt. A circuit would provide an output voltage within each of these 10 ranges. An input of a circuit would need to determine in which of the 10 ranges an applied voltage lies. If we wish to allow for noise on the voltages, then output voltage might be permitted to range over less than 0.05 volt for a given digit representation, and boundaries between inputs could vary by less than 0.05 volt. This would require complex and costly electronic circuits, and the output still could be disturbed by small "noise" voltages or small variations in the circuits occurring during their manufacture or use. As a consequence, the use of such multivalued circuits is very limited. Instead, binary circuits are used in which correct circuit

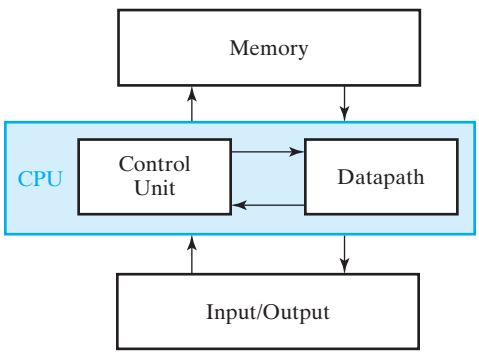
operation can be achieved with significant variations in values of the two output voltages and the two input ranges. The resulting transistor circuit with an output that is either HIGH or LOW is simple, easy to design, and extremely reliable. In addition, this use of binary values makes the results calculated repeatable in the sense that the same set of input values to a calculation always gives exactly the same set of outputs. This is not necessarily the case for multivalued or analog circuits, in which noise voltages and small variations due to manufacture or circuit aging can cause results to differ at different times.

The Digital Computer

A block diagram of a digital computer is shown in Figure 1-2. The memory stores programs as well as input, output, and intermediate data. The datapath performs arithmetic and other data-processing operations as specified by the program. The control unit supervises the flow of information between the various units. A datapath, when combined with the control unit, forms a component referred to as a *central processing unit*, or CPU.

The program and data prepared by the user are transferred into memory by means of an input device such as a keyboard. An output device, such as an LCD (liquid crystal display), displays the results of the computations and presents them to the user. A digital computer can accommodate many different input and output devices, such as DVD drives, USB flash drives, scanners, and printers. These devices use digital logic circuits, but often include analog electronic circuits, optical sensors, LCDs, and electromechanical components.

The control unit in the CPU retrieves the instructions, one by one, from the program stored in the memory. For each instruction, the control unit manipulates the datapath to execute the operation specified by the instruction. Both program and data are stored in memory. A digital computer can perform arithmetic computations, manipulate strings of alphabetic characters, and be programmed to make decisions based on internal and external conditions.

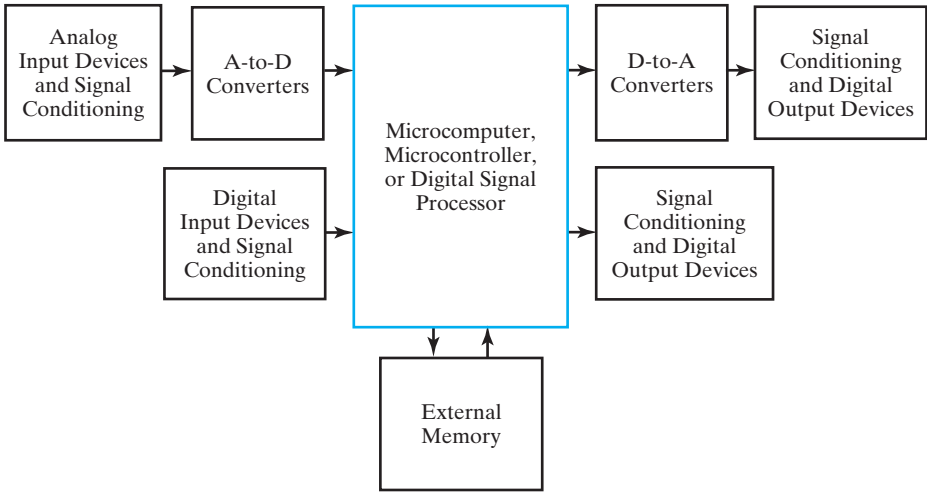


□ **FIGURE 1-2**
Block Diagram of a Digital Computer

Beyond the Computer

In terms of world impact, computers, such as the PC, are not the end of the story. Smaller, often less powerful, single-chip computers called *microcomputers* or *microcontrollers*, or special-purpose computers called *digital signal processors* (DSPs) actually are more prevalent in our lives. These computers are parts of everyday products and their presence is often not apparent. As a consequence of being integral parts of other products and often enclosed within them, they are called *embedded systems*. A generic block diagram of an embedded system is shown in Figure 1-3. Central to the system is the microcomputer (or its equivalent). It has many of the characteristics of the PC, but differs in the sense that its software programs are often permanently stored to provide only the functions required for the product. This software, which is critical to the operation of the product, is an integral part of the embedded system and referred to as *embedded software*. Also, the human interface of the microcomputer can be very limited or nonexistent. The larger information-storage components such as a hard drive and compact disk or DVD drive frequently are not present. The microcomputer contains some memory; if additional memory is needed, it can be added externally.

With the exception of the external memory, the hardware connected to the embedded microcomputer in Figure 1-3 interfaces with the product and/or the outside world. The input devices transform inputs from the product or outside world into electrical signals, and the output devices transform electrical signals into outputs to the product or outside world. The input and output devices are of two types, those which use analog signals and those which use digital signals. Examples of digital input devices include a limit switch which is closed or open depending on whether a force is applied to it and a keypad having ten decimal integer buttons. Examples of



☐ **FIGURE 1-3**
Block Diagram of an Embedded System

analog input devices include a thermistor which changes its electrical resistance in response to the temperature and a crystal which produces a charge (and a corresponding voltage) in response to the pressure applied. Typically, electrical or electronic circuitry is required to "condition" the signal so that it can be read by the embedded system. Examples of digital output devices include relays (switches that are opened or closed by applied voltages), a stepper motor that responds to applied voltage pulses, or an LED digital display. Examples of analog output devices include a loudspeaker and a panel meter with a dial. The dial position is controlled by the interaction of the magnetic fields of a permanent magnet and an electromagnet driven by the voltage applied to the meter.

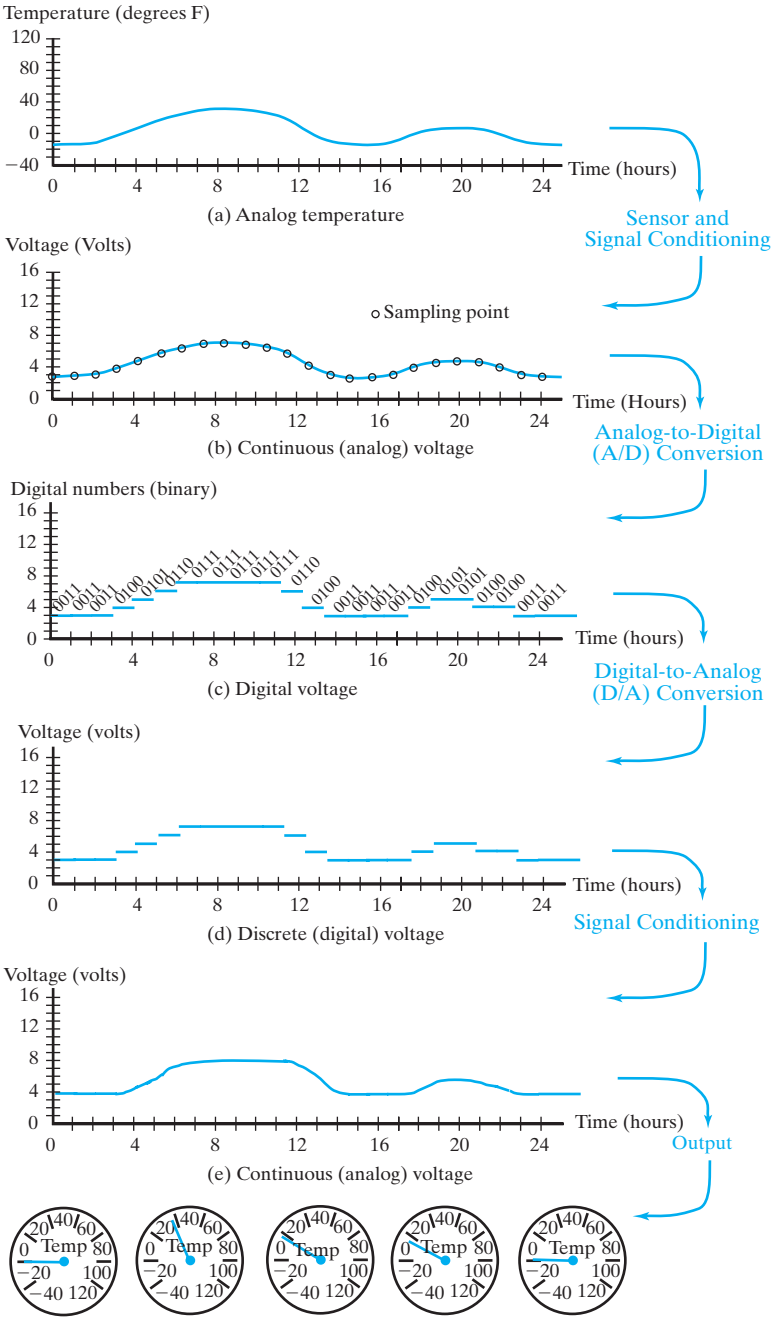
Next, we illustrate embedded systems by considering a temperature measurement performed by using a wireless weather station. In addition, this example also illustrates analog and digital signals, including conversion between the signal types.

EXAMPLE 1-1 Temperature Measurement and Display

A wireless weather station measures a number of weather parameters at an outdoor site and transmits them for display to an indoor base station. Its operation can be illustrated by considering the temperature measurement illustrated in Figure 1-4 with reference to the block diagram in Figure 1-3. Two embedded microprocessors are used, one in the outdoor site and the other in the indoor base station.

The temperature at the outdoor site ranges continuously from −40°F to +115°F. Temperature values over one 24-hour period are plotted as a function of time in Figure 1-4(a). This temperature is measured by a sensor consisting of a thermistor (a resistance that varies with temperature) with a fixed current applied by an electronic circuit. This sensor provides an analog voltage that is proportional to the temperature. Using signal conditioning, this voltage is changed to a continuous voltage ranging between 0 and 15 volts, as shown in Figure 1-4(b).

The analog voltage is sampled at a rate of once per hour (a very slow sampling rate used just for illustration), as shown by the dots in Figure 1-4(b). Each value sampled is applied to an analog-to-digital (A/D) converter, as in Figure 1-3, which replaces the value with a digital number written in binary and having decimal values between 0 and 15, as shown in Figure 1-4(c). A binary number can be interpreted in decimal by multiplying the bits from left to right times the respective weights, 8, 4, 2, and 1, and adding the resulting values. For example, 0101 can be interpreted as $0 \times 8 + 1 \times 4 + 0 \times 2 + 1 \times 1 = 5$. In the process of conversion, the value of the temperature is quantized from an infinite number of values to just 16 values. Examining the correspondence between the temperature in Figure 1-4(a) and the voltage in Figure 1-4(b), we find that the typical digital value of temperature represents an actual temperature range up to 5 degrees above or below the digital value. For example, the analog temperature range between −25 and −15 degrees is represented by the digital temperature value of −20 degrees. This discrepancy between the actual temperature and the digital temperature is called the *quantization error*. In order to obtain greater precision, we would need to increase the number of bits beyond four in the output of the A/D converter. The hardware components for sensing, signal conditioning, and A/D conversion are shown in the upper left corner of Figure 1-3.



□ **FIGURE 1-4**
Temperature Measurement and Display