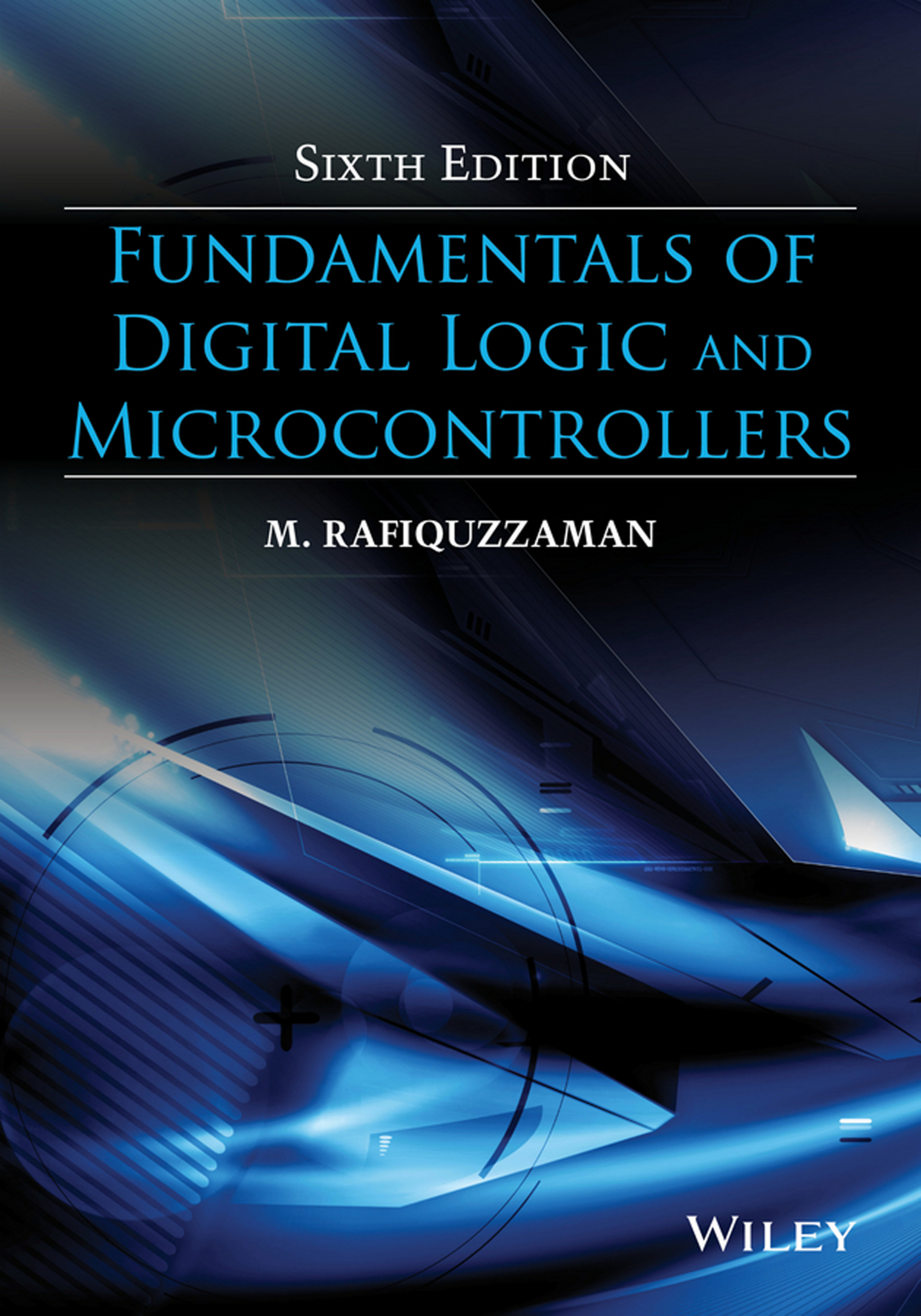
Sixth Edition
Fundamentals of Digital Logic and Microcontrollers
M. Rafiquzzaman
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Fundamentals of Digital Logic and Microcontrollers

Sixth Edition

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WILEY

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10 9 8 7 6 5 4 3 2 1

To my wife, Kusum; son, Tito; daughter-in-law,
Trina; and my grandchildren

In memory of my brother Elan

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PREFACE

The fifth edition of the book covered basics of computer engineering and science from digital logic to the design of a complete microcomputer system using Intel 8086 and Motorola 68000. With the growing popularity of microcontrollers, it is now necessary to have a clear understanding of the basic principles of microcontrollers at the undergraduate level. Microcontrollers play an important role in the design of digital systems. They are found in a wide range of applications including office automation systems such as copiers and fax machines, consumer electronics such as microwave ovens, digital instruments, and robotics.

Hence, a typical microcontroller such as Microchip Technology's PIC18F is used to replace the 8086 and 68000 in this edition. Several PIC18F-based simple practical applications using C-language are provided. The sixth edition covers an enhanced version of both combinational and sequential logic design, basics of computer organization and microcontrollers.

Like the fifth edition, emphasis is given on the basic concepts. To cite an example, we clearly point out that computers understand only 0's and 1's. It is, therefore, important that students be familiar with binary numbers. Furthermore, we focus on the fact that computers can normally only add. Hence, all other arithmetic operations such as subtraction are performed via addition. This can be accomplished using two's-complement arithmetic for binary numbers. This topic is, therefore, also included along with a clear explanation of signed and unsigned binary numbers. Basic concepts such as this are illustrated with simple examples throughout this edition.

As in the previous edition, three design levels are covered in this book: device level, logic level, and system level. Device-level design using simple devices such as transistors is included for typical logic gates such as NOT. Logic-level design is the technique in which logic gates are used; design of digital components such as an adder is provided. Finally, system-level applications are covered using a typical microcontroller such as the PIC18F.

Digital systems at the logic level are classified into two types of circuits: combinational and sequential. Combinational circuits have no memory whereas sequential circuits contain memory. Microcontrollers are designed using both combinational and sequential circuits. Therefore, these topics are covered in detail.

This edition of the book contains more details for synthesizing digital logic circuits using a popular hardware description language such as Verilog. An overview of contemporary digital circuit implementation using a popular programmable logic device (PLD) such as field programmable gate array (FPGA) along with the CAD (computer aided design) tools is included.

Several chapters in the previous edition containing digital logic design have been retained and even strengthened in this edition. A few chapters of this new edition are written to present the fundamental concepts of C language programming and interfacing techniques associated with Microchip Technology's PIC18F4321 microcontroller. The PIC18F family continues to be popular. The PIC18F family is an excellent educational tool for acquiring an understanding of both hardware and software aspects of typical microcontrollers.

Several PIC18F-based simple practical applications using C-language are provided. Most of the examples are implemented successfully in the laboratory. In summary, the sixth edition covers an enhanced version of both combinational and sequential logic, basics of computer organization, and microcontrollers.
The following major changes have been provided in this edition:

- Revised Chapters 1 through 5 of the fifth edition to update and strengthen certain topics on both combinational and sequential circuits. Several new examples are included. In addition, certain topics such as timing diagrams, hazards, stability, and Verilog and FPGA are enhanced.
- Chapter 6 of this edition contains design of the CPU, memory, and I/O. Design of both hardwired and microprogrammed CPU is included.
- Chapters 7 through 9 of this edition include microcontroller basics and PIC18F-based applications using C.

In this edition, the book is divided into nine chapters as follow:

Chapter 1 presents an explanation of basic terminologies, fundamental concepts of digital integrated circuits using transistors; a comparison of LSTTL, HC, and HCT IC characteristics, evolution of the microcontroller, and technological forecasts.

Chapter 2 includes various number systems and codes suitable for representing information in typical digital systems.

Chapter 3 covers Boolean algebra along with k-map simplification of Boolean functions. Several examples are included. The basic characteristics of digital logic gates are also presented.

Chapter 4 presents the analysis and design of combinational circuits. Typical combinational circuits such as adder, decoder, encoder, multiplexer, demultiplexer, and ROMs are included. An introduction to PLDs and FPGA is provided. Synthesis of combinational logic design using Verilog is also included.

Chapter 5 covers various types of flip-flops. Analysis and design of sequential circuits such as counters and registers are covered. An overview of topics such as flip-flop set-up time, hold time, and metastability is provided. Finally, synthesis of sequential logic design using Verilog is included.

Chapter 6 introduces basic concepts associated with CPU, memory, and I/O. It also covers the design of CPU including registers, ALU, and the control unit.

Chapter 7 presents basics of microcontroller including organization, memory, I/O, and C programming concepts.

Chapter 8 provides typical C programs which include I/O examples with LEDs and switches. PIC18F-based programmed and interrupt I/O using C are covered in a simplified manner.

Chapter 9 contains simple PIC18F-based applications using C. These include A/D and D/A converters, LCD displays, on-chip timers, DC voltmeter, and motor control using PWM (pulse width modulation).

The book can easily be adopted as a text for "digital logic design" and/or "introduction to microcontrollers" at the undergraduate level in electrical/computer engineering and computer science. The book introduces microcontroller hardware and software to form a bridge between digital logic and an advanced follow-up course in microcontrollers. The book provides an introduction to one of today's popular microcontrollers, the PIC18F family. Although no advanced mathematical background is required, a basic course on DC circuits is required. A first course in C language programming is essential. Since C language programming is prerequisite for the course on microcontrollers, I/O and interfacing using C is included in this book. The audience for this book can also be practicing engineers and scientists in the industry. Practitioners of digital system design in the industry will find more simplified explanations, together with examples and comparison considerations, than are found in manufacturers' manuals.

The author is especially indebted to his colleague, Dr. R. Chandra, of California State Polytechnic University, Pomona for reviewing the manuscript. The author is also grateful to his students Robert Benenyan, Michael Hachache, Cameron Chitsaz, Gagneet Bhatia, Luke Stankiewicz, and others for making constructive suggestions and to CJ Media of California for preparing the final version of the manuscript. Finally, the author is indebted to his deceased parents, who were primarily responsible for his accomplishments.

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Pomona, California

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1
INTRODUCTION TO DIGITAL SYSTEMS

Digital systems are designed to store, process, and communicate information in digital form. They are found in a wide range of applications, including process control, communication systems, digital instruments, and consumer products. The digital computer, more commonly called the *computer*, is an example of a typical digital system.

A computer manipulates information in digital, or more precisely, binary form. A binary number has only two discrete values — zero or one. Each of these discrete values is represented by the OFF and ON status of an electronic switch called a *transistor*. All computers, therefore, only understand binary numbers. Any decimal number (base 10, with ten digits from 0 to 9) can be represented by a binary number (base 2, with digits 0 and 1).

The basic blocks of a computer are the central processing unit (CPU), the memory, and the input/output (I/O). The CPU of the computer is basically the same as the brain of a human. Computer memory is conceptually similar to human memory. A question asked to a human is analogous to entering a program into the computer using an input device such as the keyboard, and answering the question by the human is similar in concept to outputting the result required by the program to a computer output device such as the printer. The main difference is that human beings can think independently, whereas computers can only answer questions that they are programmed for. Computer hardware refers to components of a computer such as memory, CPU, transistors, nuts and bolts. Programs can perform a specific task such as addition if the computer has an electronic circuit capable of adding two numbers. Programmers cannot change these electronic circuits but can perform tasks on them using instructions.

Computer software, on the other hand, consists of a collection of programs. Programs contain instructions and data for performing a specific task. These programs, written using any programming language such as C, must be translated into binary prior to execution by the computer. This is because the computer only understands binary numbers. Therefore, a translator for converting such a program into binary is necessary. Hence, a translator program called the *compiler* is used for translating programs written in a programming language such as C into binary. These programs in binary form are then stored in the computer memory for execution because computers only understand 1's and 0's. Furthermore, computers can only add. This means that all operations such as subtraction, multiplication, and division are performed by addition.

Due to advances in semiconductor technology, it is possible to fabricate the CPU in a single chip. The result is the *microprocessor*. Both metal oxide semiconductor (MOS) and bipolar technologies were used in the fabrication process. The CPU can be placed on a single chip when MOS technology is used. However, several chips are

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required with the bipolar technology. HCMOS (high speed complementary MOS) or BICMOS (combination of bipolar and HCMOS) technology (to be discussed later in this chapter) is normally used these days to fabricate the microprocessor in a single chip. Along with the microprocessor chip, appropriate memory and I/O chips can be used to design a *microcomputer*. The pins on each one of these chips can be connected to the proper lines on the system bus, which consists of address, data, and control lines. In the past, some manufacturers have designed a complete microcomputer on a single chip with limited capabilities. Single-chip microcomputers were used in a wide range of industrial and home applications.

"Microcontrollers" evolved from single-chip microcomputers. The microcontrollers are typically used for dedicated applications such as automotive systems, home appliances, and home entertainment systems. Typical microcontrollers, therefore, include a microcomputer, timers, and A/D (analog to digital) and D/A (digital to analog) converters — all in a single chip. Examples of typical microcontrollers are Intel 8751 (8-bit) / 8096 (16-bit) and Motorola/Freescale HC11 (8-bit) / HC16 (16-bit), and Microchip Technology PIC18F(8-bit)/PIC32(32-bit).

In this chapter, we first define some basic terms associated with the computers. We then describe briefly the evolution of the computers and the microcontrollers. Finally, a typical practical application, and technological forecasts are included.

1.1 Explanation of Terms

Before we go on, it is necessary to understand some basic terms (arranged in alphabetical order).

- *Address* is a pattern of 0's and 1's that represents a specific location in memory or a particular I/O device. An 8-bit microcontroller with 16 address bits can produce 2^{16} unique 16-bit patterns from 0000000000000000 to 1111111111111111, representing 65,536 different address combinations (addresses 0 to 65,535).
- *Addressing mode* is the manner in which the microcontroller determines the operand (data) and destination addresses during execution of an instruction.
- *Arithmetic-logic unit* (ALU) is a digital circuit that performs arithmetic and logic operations on two *n*-bit digital words. Typical operations performed by an ALU are addition, subtraction, ANDing, ORing, and comparison of two *n*-bit digital words. The size of the ALU defines the size of the microcontroller. For example, an 8-bit microcontroller contains an 8-bit ALU.
- *Big endian* convention is used to store a 16-bit number such as 16-bit data in two bytes of memory locations as follows: the low memory address stores the high byte while the high memory address stores the low byte. The Motorola/Freescale HC11 8-bit microcontroller follows the big endian format.
- *Bit* is an abbreviation for the term *binary digit*. A binary digit can have only two values, which are represented by the symbols 0 and 1, whereas a decimal digit can have 10 values, represented by the symbols 0 through 9. The bit values are easily implemented in electronic and magnetic media by two-state devices whose states portray either of the binary digits 0 and 1. Examples of such two-state devices are a transistor that is conducting or not conducting, a capacitor that is charged or discharged, and a magnetic material that is magnetized north to south or south to north.

- *Bit size* refers to the number of bits that can be processed simultaneously by the basic arithmetic circuits of a microcontroller. A number of bits taken as a group in this manner is called a *word*. For example, an 8-bit microcontroller can process an 8-bit word. An 8-bit word is referred to as a *byte*, and a 4-bit word is known as a *nibble*.
- *Bus* consists of a number of conductors (wires) grouped to provide a means of communication among different elements in a microcontroller system. The conductors in a bus can be grouped in terms of their functions. A microcontroller normally has an address bus, a data bus, and a control bus. Address bits are sent to memory or to an external device on the *address bus*. Instructions from memory, and data to/from memory or external devices, normally travel on the *data bus*. Control signals such as read/write for the other buses and among system elements are transmitted on the *control bus*. Buses are sometimes *bidirectional*; that is, information can be transmitted in either direction on the bus, but normally in only one direction at a time.
- *Clock* is analogous to human heart beats. The microcontroller requires synchronization among its components, and this is provided by a *clock* or timing circuits.
- The *chip* is an integrated circuit (IC) package containing digital circuits.
- *CPU* (central processing unit) contains several registers (memory elements), an ALU, and a control unit. Note that the control unit translates instructions and performs the desired task. The number of peripheral devices depends on the particular application involved and may even vary within an application.
- *EEPROM* or *E^2PROM* (electrically erasable programmable ROM) is nonvolatile. EEPROMs can be programmed without removing the chip from the socket. EEPROMs are called read most memories (RMMs) because they have much slower write times than read times. Therefore, these memories are usually suited for applications when mostly reading rather than writing is performed. An example of EEPROM is the 2864 (8K x 8).
- *EPROM* (erasable programmable ROM) is nonvolatile. EPROMs can be programmed and erased. The EPROM chip must be removed from the socket for programming. This memory is erased by exposing the chip to ultraviolet light via a lid or window on the chip. Typical erase times vary between 10 and 30 minutes. The EPROM is programmed by inserting the chip into a socket of the EPROM programmer, and providing proper addresses and voltage pulses at the appropriate pins of the chip. An example of EPROM is the 2764 (8K $\times$ 8).
- *Flash memory* is designed using a combination of EPROM and EEPROM technologies. Flash memory is nonvolatile and is invented by Toshiba in mid 1980s. Flash memory can be programmed electrically while embedded on the board. One can change multiple bytes at a time. An example of flash memory is the Intel 28F020 (256K x 8). Flash memory is typically used in cell phones and digital cameras.
- An *FPGA* (field programmable gate array) chip contains an array of digital logic blocks along with input and output blocks which can be connected together via programming using a hardware description language (HDL) such as Verilog or

VHDL. There are two types of components inside an FPGA. These are lookup table (stored in memory), and switch matrices. The concept of FPGA is based on the fact that a combinational circuit can be implemented using memory. In the past, digital logic circuits were built using all hardware (logic gates). It was a time-consuming task to debug the circuits. However, digital circuits implemented using FPGA's are faster to debug since they are programmable. Note that it is much faster to debug software than hardware. Hence, products can be developed using FPGA from conceptual design via prototype to production in a very short time. Therefore, use of FPGA in digital logic is very common these days.

- The term *gate* refers to digital circuits which perform logic operations such as AND, OR, and NOT. In an AND operation, the output of the AND gate is one if all inputs are one; the output is zero if one or more inputs are zero. The OR gate, on the other hand, provides a zero output if all inputs are zero; the output is one if one or more inputs are one. Finally, a NOT gate (also called an *inverter*) has one input and one output. The NOT gate produces one if the input is zero; the output is zero if the input is one.
- *Harvard architecture* is a type of CPU architecture which uses separate instruction and data memory units along with separate buses for instructions and data. This means that these processors can execute instructions and access data simultaneously. Processors designed with this architecture require four buses for program memory and data memory. These are one data bus for instructions, one address bus for addresses of instructions, one data bus for data, and one address bus for addresses of data. The sizes of the address and data buses for instructions may be different from the address and data buses for data. Several microcontrollers including the PIC18F are designed using the Harvard architecture. This is because it is inexpensive to implement these buses inside the chip since both program and data memories are internal to the chip.
- *Instruction set* of a microcontroller is a list of commands that the microcontroller is designed to execute. Typical instructions are ADD, SUBTRACT, and STORE. Individual instructions are coded as unique bit patterns which are recognized and executed by the microcontroller. If a microcontroller has three bits allocated to the representation of instructions, the microcontroller will recognize a maximum of 2^3, or eight, different instructions. The microcontroller will then have a maximum of eight instructions in its instruction set. It is obvious that some instructions will be more suitable than others to a particular application. For example, in a control application, instructions inputting digitized signals to the processor and outputting digital control variables to external circuits are essential. The number of instructions necessary in an application will directly influence the amount of hardware in the chip set and the number and organization of the interconnecting bus lines.
- *Little endian* convention is used to store a 16-bit number such as 16-bit data in two bytes of memory locations as follows: the low memory address stores the low byte while the high memory address stores the high byte. The PIC18F microcontroller follows the little-endian format.
- *Microcomputer* typically consists of a microprocessor (CPU) chip, input and output chips, and memory chips in which programs (instructions and data) are stored.

- *Microcontroller* is implemented on a single chip containing a CPU, memory, and IOP (I/O and peripherals). Note that a typical IOP contains I/O unit of a microcomputer, timers, A/D (analog-to-digital) converter, analog comparators, serial I/O, and other peripheral functions (to be discussed later).
- *Microprocessor* is the CPU of a microcomputer contained in a single chip, and must be interfaced with peripheral support chips in order to function.
- *Pipelining* is a technique that overlaps instruction fetch (instruction read) with execution. This allows a microcontroller's processing operation to be broken down into several steps (dictated by the number of pipeline levels or stages) so that the individual step outputs can be handled by the microcontroller in parallel. Pipelining is often used to fetch the microcontroller's next instruction while executing the current instruction, which speeds up the overall operation of the microcontroller considerably. Microchip technology's PIC18F (8-bit microcontroller) uses a two-stage instruction pipeline in order to speed up instruction execution.
- *Program* contains instructions and data. Two conventions are used to store a 16-bit number such as 16-bit data in two bytes of memory locations. These are called *little endian* and *big endian byte ordering.* In little endian convention, the low memory address stores the low byte while the high memory address stores the high byte. For example, the 16-bit hexadecimal number, 2050 will be stored as two bytes in two 16-bit locations (Hex 5000 and Hex 5001) as follows: Address 5000 will contain 50 while address 5001 will store 20. In big endian convention, on the other hand, the low memory address stores the high byte while the high memory address stores the low byte. For example, the same 16-bit hexadecimal number, 2050 will be stored as two bytes in two 16-bit locations (Hex 5000 and Hex 5001) as follows: Address 5000 will contain 20 while address 5001 will store 50. Motorola / Freescale HC11 (8-bit microcontroller) follows big endian convention. Microchip PIC18F (8-bit microcontroller), on the other hand, follows the little endian format.
- *Random-access memory* (RAM) is a storage medium for groups of bits or words whose contents cannot only be read but can also be altered at specific addresses. A RAM normally provides *volatile storage*, which means that its contents are lost in case power is turned off. There are two types of RAM: static RAM (SRAM) and dynamic RAM (DRAM). *Static RAM* stores data in flip-flops. Therefore, this memory does not need to be refreshed. An example of SRAM is 6116 (2K $\times$ 8). *Dynamic RAM*, on the other hand, stores data in capacitors. That is, it can hold data for a few milliseconds. Hence, dynamic RAMs are refreshed typically by using external refresh circuitry. Dynamic RAMs (DRAMs) are used in applications requiring large memory. DRAMs have higher densities than static RAMs (SRAMs). Typical examples of DRAMs are the 4464 (64K $\times$ 4), 44256 (256K $\times$ 4), and 41000 (1M $\times$ 1). DRAMs are inexpensive, occupy less space, and dissipate less power than SRAMs.
- *Read-only memory* (ROM) is a storage medium for the groups of bits called *words*, and its contents cannot normally be altered once programmed. A typical ROM is fabricated on a chip and can store, for example, 2048 eight-bit words, which can be accessed individually by presenting to it one of 2048 addresses. This ROM is referred to as a *2K by 8-bit ROM*. 10110111 is an example of an 8-bit word that might be stored in one location in this memory. A ROM is a *nonvolatile storage*

device, which means that its contents are retained in case power is turned off. Because of this characteristic, ROMs are used to store permanent programs (instructions and data).

- *Reduced Instruction Set Computer* (RISC) contains a simple instruction set. In contrast, a *Complex Instruction Set Computer* (CISC) contains a large instruction set. The PIC18F is an RISC-based microcontroller while Motorola/Freescale HC11 is a CISC-based microcontroller.
- *Register* can be considered as volatile storage for a number of bits. These bits may be entered into the register simultaneously (in parallel) or sequentially (serially) from right to left or from left to right, 1-bit at a time. An 8-bit register storing the bits 11110000 is represented as follows:

1	1	1	1	0	0	0	0

- The *speed power product* (*SPP*) is a measure of performance of a logic gate. It is expressed in picojoules (pJ). SPP is obtained by multiplying the speed (ns) by the power dissipation (mW) of a gate.
- *Transistors* are basically electronic switching devices. There are two types of transistors. These are *bipolar junction transistors* (*BJTs*) and *metal-oxide semiconductor* (*MOS*) transistors. The operation of the BJT depends on the flow of two types of carriers: electrons (*n*-channel) and holes (*p*-channel), whereas the MOS transistor is unipolar and its operation depends on the flow of only one type of carrier, either electrons (*n*-channel) or holes (*p*-channel).
- *von Neumann* (*Princeton*) *architecture* uses a single memory unit and the same bus for accessing both instructions and data. Although CPUs designed using this architecture are slower compared to Harvard architecture since instructions and data cannot be accessed simultaneously because of the single bus, typical microprocessors such as the Pentium use this architecture. This is because memory units such as ROMs, EPROMs, and RAMs are external to the microprocessor. This will require almost half the number of wires on the mother board since address and data pins for only two buses rather than four buses (Harvard architecture) are required. This is the reason Harvard architecture would be very expensive if utilized in designing microprocessors. Note that microcontrollers using Harvard architecture internally will have to use von Neumann architecture externally. Texas Instrument's MSP 430 uses the von Neumann architecture.

1.2 Design Levels

Three design levels can be defined for digital systems: systems level, logic level, and device level.

- *Systems level* is the type of design in which CPU, memory, and I/O chips are interfaced to build a computer.
- *Logic level* is the design technique in which chips containing logic gates such as AND, OR, and NOT are used to design a digital component such as the ALU.
- Finally, *device level* utilizes transistors to design logic gates.

1.3 Combinational and Sequential Circuits

Digital circuits at the logic level can be classified into two types. These are *combinational and sequential.*

Combinational circuits contain no memory, whereas sequential circuits require memory to remember the present state in order to go to the next state. A binary adder capable of providing the sum upon application of the numbers to be added is an example of a combinational circuit. For example, consider a 4-bit adder. The inputs to this adder will be two 4-bit numbers; the output will be the 4-bit sum. In this case, the adder will generate the 4-bit sum output upon application of the two 4-bit inputs.

Sequential circuits, on the other hand, require memory. The counter is an example of a sequential circuit. For instance, suppose that the counter is required to count in the sequence 0, 1, 2 and then repeat the sequence. In this case, the counter must have memory to remember the present count in order to go to the next. The counter must remember that it is at count 0 in order to go to the next count, 1. In order to count to 2, the counter must remember that it is counting 1 at the present state. In order to repeat the sequence, the counter must count back to 0 based on the present count, 2, and the process continues. A chip containing sequential circuit such as the counter will have a clock input pin.

In general, all computers contain both combinational and sequential circuits. However, most computers are regarded as clocked sequential systems. In these computers, almost all activities pertaining to instruction execution are synchronized with clocks.

1.4 Digital Integrated Circuits

The transistor can be considered as an electronic switch. The ON and OFF states of a transistor are used to represent binary digits. Transistors, therefore, play an important role in the design of digital systems. This section describes the basic characteristics of digital devices and logic families. These include diodes, transistors, and a summary of digital logic families. These topics are covered from a very basic point of view. This will allow the readers with some background in digital devices to see how they are utilized in designing digital systems.

1.4.1 Diodes

A diode is an electronic switch. It is a two-terminal device. Figure 1.1 shows the symbolic representation.

The positive terminal (made with the *p*-type semiconductor material) is called the *anode*; the negative terminal (made with the *n*-type semiconductor material) is called a *cathode*. When a voltage, $V = 0.6$ volt is applied across the anode and the cathode, the switch closes and a current I flows from anode to the cathode.

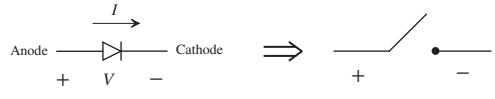
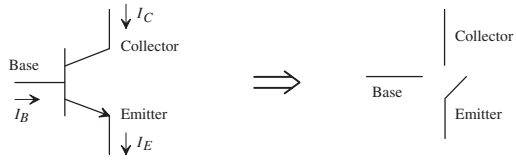


FIGURE 1.1 Symbolic representations of a diode.



(a) *npn* Transistor symbol (b) Equivalent circuit

FIGURE 1.2 (a and b) Symbolic representations of an *npn* transistor.

1.4.2 Transistors

A bipolar junction transistor (BJT) or commonly called the *transistor* is also an electronic switch like the diode. Both electrons (*n*-channel) and holes (*p*-channel) are used for carrier flow; hence, the name "bipolar" is used. The BJT is used in transistor logic circuits that have several advantages over diode logic circuits. First of all, the transistor acts as a logic device called an *inverter*. Note that an inverter provides a LOW output for a HIGH input and a HIGH output for a LOW input. Secondly, the transistor is a current amplifier (buffer). Transistors can, therefore, be used to amplify these currents to control external devices such as a light emitting diode (LED) requiring high currents. Finally, transistor logic gates operate faster than diode gates.

There are two types of transistors, namely *npn* and *pnp*. The classification depends on the fabrication process. *npn* transistors are widely used in digital circuits.

Figure 1.2 shows the symbolic representation of an *npn* transistor. The transistor is a three-terminal device. These are base, emitter, and collector. The transistor is a current-controlled switch. This means that an adequate current at the base will close the switch allowing a current to flow from the collector to the emitter.

This current direction is identified on the *npn* transistor symbol in Figure 1.2(a) by a downward arrow on the emitter. Note that a base resistance is normally required to generate the base current.

The transistor has three modes of operation: cutoff, saturation, and active. In digital circuits, a transistor is used as a switch, which is either ON (closed) or OFF (open). When no base current flows, the emitter-collector switch is open and the transistor operates in the cutoff (OFF) mode. On the other hand, when a base current flows such that the voltage across the base and the emitter is at least 0.6 V, the switch closes. If the base current is further increased, there will be a situation in which V_{CE} (voltage across the collector and the emitter) attains a constant value of approximately 0.2 V. This is called the saturation (ON) mode of the transistor. The "active" mode is between the cutoff and saturation modes. In this mode, the base current (I_B) is amplified so that the collector current, $I_C = \beta I_B$, where β is called the gain, and is in the range of 10 to 100 for typical transistors. Note that when the transistor reaches saturation, increasing I_B does not drop V_{CE} below $V_{CE\,(\text{Sat.})}$ of 0.2 V. On the other hand, V_{CE} varies from 0.8 V to 5 V in the active mode. Therefore, the cutoff (OFF) and saturation (ON) modes of the transistor are used in designing digital circuits. The active mode of the transistor in which the transistor acts as a current amplifier (also called *buffer*) is used in digital output circuits.

Operation of the Transistor as an Inverter Figure 1.3 shows how to use the transistor as an inverter. When $V_{IN} = 0$, the transistor is in cutoff (OFF), and the collector-emitter switch is open. This means that no current flows from $+V_{CC}$ to ground. V_{OUT} is equal to $+V_{CC}$. Thus, V_{OUT} is high.

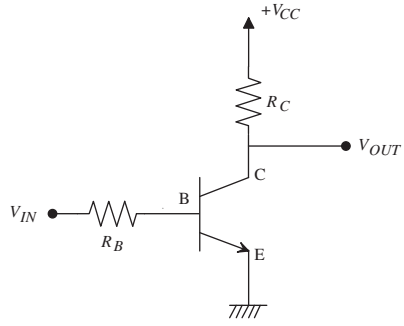


FIGURE 1.3 An inverter.

On the other hand, when V_{IN} is HIGH, the emitter-collector switch is closed. A current flows from $+V_{CC}$ to ground. The transistor operates in saturation, and $V_{OUT} = V_{CE\,(Sat)} = 0.2\text{ V} \approx 0$. Thus, V_{OUT} is basically connected to ground.

Therefore, for V_{IN} = LOW, V_{OUT} = HIGH, and for V_{IN} = HIGH, V_{OUT} = LOW. Hence, the *npn* transistor in Figure 1.3 acts as an inverter.

Note that V_{CC} is typically +5 V DC. The input voltage levels are normally in the range of 0 to 0.8 volts for LOW and 2 volts to 5 volts for HIGH. The output voltage levels, on the other hand, are normally 0.2 volts for LOW and 3.6 volts for HIGH.

Light Emitting Diodes (LEDs) and Seven Segment Displays LEDs are extensively used as outputs in digital systems as status indicators. An LED is typically driven by low voltage and low current. This makes the LED a very attractive device for use with digital systems. Table 1.1 provides the current and voltage requirements of red, yellow, and green LEDs.

Basically, an LED will be ON, generating light, when its cathode is sufficiently negative with respect to its anode. A digital system such as a microcomputer can, therefore, light an LED either by grounding the cathode (if the anode is tied to +5 V) or by applying +5 V to the anode (if the cathode is grounded) through an appropriate resistor value. A typical hardware interface between a microcomputer and an LED is depicted in Figure 1.4. A microcomputer normally outputs 400 μA at a minimum

TABLE 1.1 Current and voltage requirements of LEDs

LEDs	Red	Yellow	Green
Current	10 mA	10 mA	20 mA
Voltage	1.7 V	2.2V	2.4V

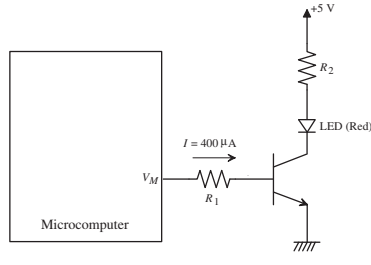


FIGURE 1.4 Microcomputer - LED interface.