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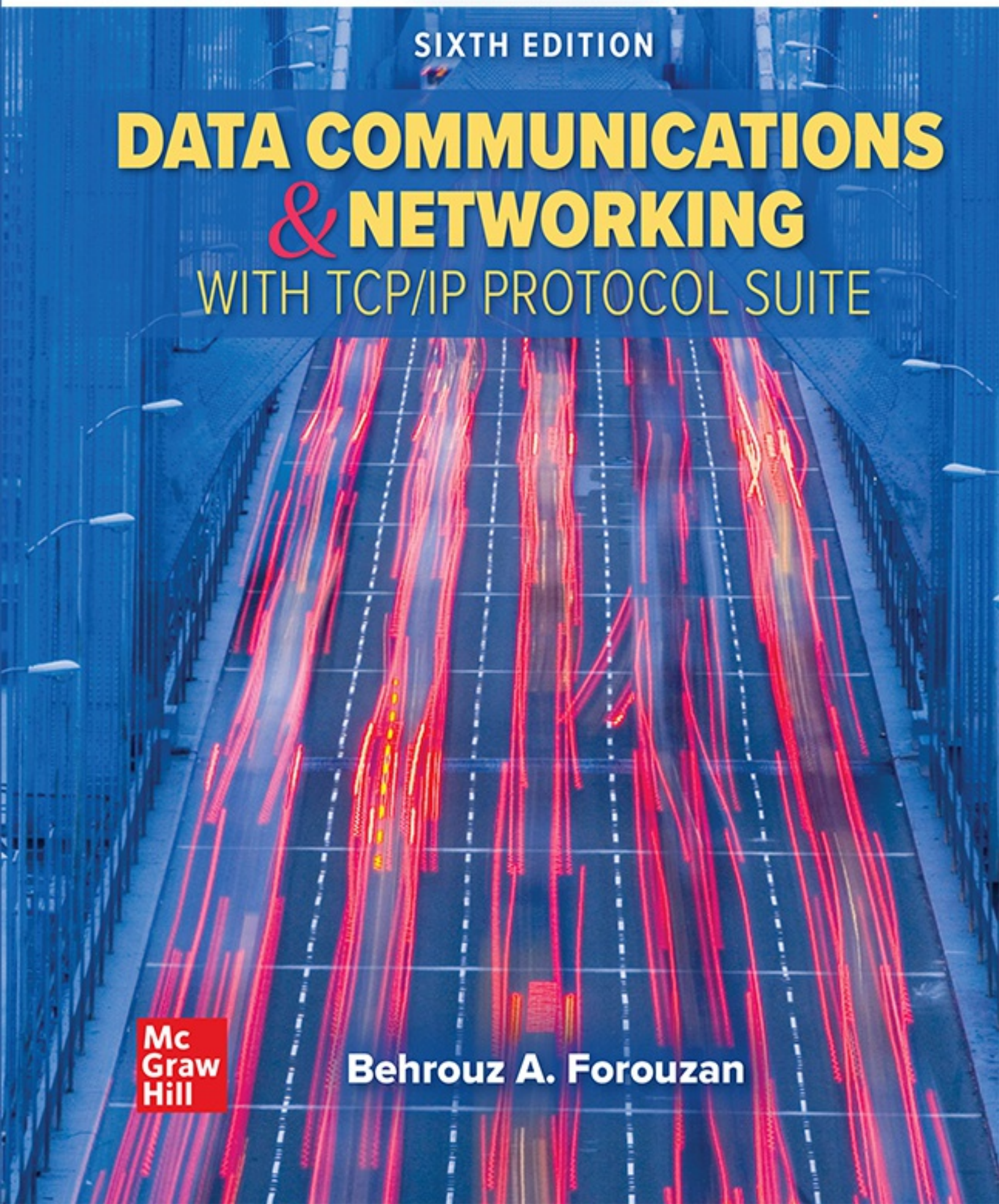

SIXTH EDITION

DATA COMMUNICATIONS & NETWORKING

WITH TCP/IP PROTOCOL SUITE

Behrouz A. Forouzan

Mc Graw Hill

Data Communications and Networking with TCP/IP Protocol Suite

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To my beloved daughter.

BRIEF CONTENTS

CONTENTS

Chapter 2 *Physical Layer*

Chapter 7 *Network Layer: Data Transfer*

Appendices

PREFACE

Welcome to the sixth edition of *Data Communications and Networking with TCP/IP Protocol Suite*. We are living in an information age, and information is distributed faster that ever using the Internet, which works based on the topics discussed in this book.

Features

Although the main goal of this book is to teach the principles of networking, it is designed to teach these principles using the following features:

TCP/IP Protocol Suite

This book is designed to teach the principles of networking by using the TCP/IP protocol suite. Teaching these principles using protocol layering is beneficial because these principles are repeated and better understood in relation to each layer. For example, *addressing* is an issue that is applied to several layers of the TCP/IP protocol suite. Another example is *framing and packetizing*, which is repeated in several layers, but each layer treats the principle differently.

Bottom-Up Approach

This book uses a bottom-up approach. Each layer in the TCP/IP protocol suite is built on the services provided by the layer below. We learn how bits are moving at the physical layer (first layer) before learning how some programs exchange messages at the application layer (fifth layer).

Organization

The book is made up of 13 chapters, six appendices, a list of references, and a glossary.

Chapter 1: Introduction

This chapter is an introduction to *Data Communications and Networking with TCP/IP Protocol Suite*. It defines the concept of protocol layering and gives a brief description of the TCP/IP protocol suite and the OSI model.

Chapter 2: Physical Layer

This chapter describes the first layer of the TCP/IP protocol suite: the physical layer. It explains the relationship between data and signals and describes both analog and digital signals. It also discusses multiplexing to benefit from the available bandwidth. Finally, it goes below the physical layer and discusses the transmission media.

Chapter 3: Data-Link Layer

This chapter discusses the data-link layer, the second layer in the TCP/IP protocol suite. It shows that the data-link layer is made up of two sublayers: medial link control and data link control. It also discusses link-layer addressing.

Chapter 4: Local Area Networks: LANs

This chapter discusses the local area networks (LANs) that use only the first two layers of the TCP/IP protocol suite. It describes both wired LANs (Ethernet) and wireless LANs (WiFi and Bluetooth).

Chapter 5: Wide Area Networks: WANs

This chapter discusses the wide area networks (WANs) that also use only the first two layers of the TCP/IP protocol suite. It describes several WANs, including the telephone network, cable network, cellular telephony, and satellite networks.

Chapter 6: Connecting Devices and Virtual LANs

This chapter discusses the connecting devices such as hubs, link-layer switches, and routers. It also describes virtual LANs.

Chapter 7: Network Layer: Data Transfer

This chapter discuses the first duty of the network layer: data transfer. It explains the service in this duty such as packetizing, routing, error control, flow control, congestion control, and quality of services. It then describes the concept of packet switching. It also describe network-layer performance. The main goal is to introduce the two versions of the network layer in the Internet: IPv4 and IPv6.

Chapter 8: Network Layer: Routing Packets

This chapter discusses the second duty of the network layer: routing of packets. It discusses unicast routing protocols such as distance vector routing, link-state routing, and path-vector routing. It also discuss multicast routing and protocols.

Chapter 9: Transport Layer

This chapter discusses the transport layer. It first describes the services expected from a transfer-layer protocol. It then describes a simple transport layer protocol UDP. Finally, it describes a more sophisticated protocol TCP. Finally, it describes SCTP, a transport-layer protocol that uses association.

Chapter 10: Application Layer

This chapter discusses the application layer, the highest level in the TCP/IP protocol suite. It shows how this layer uses client/server programs. It then introduces some applications such as the Web, file transfer, and e-mail. Finally, the chapter discusses some peer-to-peer applications. It finally shows how application programs can be created using the C-language.

Chapter 11: Multimedia

This chapter discusses multimedia. It shows how compression is used in multimedia. It then defines the elements of multimedia such as text, image,

video, and audio. It then describes how multimedia is used in the Internet.

Chapter 12: Network Management

This chapter introduces network management and discusses five general areas used in network management. It also defines the Simple Network Management Protocol (SNMP) that is used in the Internet, which is based on Simple Management Information (SMI).

Chapter 13: Cryptography and Network Security

This chapter briefly discusses the concept of security goals including confidentiality, integrity, and availability. It then describes how these goals can be achieved using message integrity, message authentication, digital signature, and entity authentication. The chapter then describes how these goals can be achieved using security in the transport layer and application layer.

Appendix A

This appendix discusses Unicode, the coding system used in communication.

Appendix B

This appendix discusses the positional numbering system and how the system uses numbers in different bases.

Appendix C

This appendix discusses mark-up languages such as HTML, CSS, XML, and XSL, which are used in data communications and networking.

Appendix D

This appendix gives a touch of probability that can be useful in understanding some networking protocols.

Appendix E

This appendix discusses checksum.

Appendix F

This appendix gives the list of acronyms used in the book for quick reference.

References

The book contains a list of references for further reading.

Glossary

The Glossary provides definitions for all key terms from the text and other important terminology.

Pedagogy

Several pedagogical features of this text are designed to make it particularly easy for students to understand data communications and networking.

Visual Approach

The book presents highly technical subject matter without complex formulas by using a balance of text and figures. More than 500 figures accompanying the text provide a visual and intuitive opportunity for understanding the material. Figures are particularly important in explaining networking concepts. For many students, these concepts are more easily grasped visually than verbally.

Highlighted Points

The book repeats important concepts in boxes for quick reference and immediate attention.

Examples and Applications

Whenever appropriate, examples illustrate the concepts introduced in the text. Also, some real-life applications provided throughout each chapter help motivate students.

End-of-Chapter Materials

Each chapter ends with a set of materials that includes the following:

Key Terms

The new terms used in each chapter are listed at the end of the chapter, and their definitions are included in the glossary.

Summary

Each chapter ends with a summary of the material covered by that chapter. The summary glues the important materials together to be seen in one shot.

Recommended Reading

This section gives a brief list of references relative to the chapter. The references can be used to quickly find the corresponding literature in the reference section at the end of the book.

Practice Set

Each chapter includes a practice set designed to reinforce salient concepts and encourage students to apply them. It consists of three parts: quizzes, questions, and problems.

Quizzes

Quizzes, which are posted on the book website, provide quick concept checking.
Students can take these quizzes to check their understanding of the materials. Students receive feedback regarding their responses immediately.

Questions

This section contains simple questions about the concepts discussed in the book. Answers to the odd-numbered questions are posted on the book website to be checked by the student. There are more than 630 end-of-chapter questions.

Problems

This section contains more difficult problems that need a deeper understanding of the materials discussed in the chapter. I strongly recommend that students try to solve all of these problems. Answers to the odd-numbered problems are also posted on the book website to be checked by the student. There are more than 600 end-of-chapter problems.

Audience

This book is written for both an academic and a professional audience. It can be used as a self-study guide for interested professionals. As a textbook, it can be used for a one-semester or one-quarter course. It is designed for the last year of undergraduate study or the first year of graduate study. Although some problems at the end of the chapters require some knowledge of probability, only general mathematical knowledge taught in the first year of college is needed to study the text.

Instruction Resources

The book contains complete instruction resources that can be downloaded from the book web site **www.mhhe.com/forouzan6e**. They include:

Presentations

The site includes a set of colorful and animated PowerPoint presentations for teaching the course.

Solution to Practice Sets

Solutions to all questions and problems are provided at the book website for the use of professors who teach the course.

Student Resources

The book contains complete student resources that can be downloaded from the book site **www.mhhe.com/forouzan6e**. They include:

Quizzes

There are quizzes at the end of each chapter that can be taken by the students. Students are encouraged to take the quizzes to test their general understanding of the materials presented in the corresponding chapter.

Solutions to Odd-Numbered Practice Set Questions and Problems

Solutions to all odd-number questions and problems are provided at the book website for the use of students.

Website

The McGraw-Hill Website contains much additional material. Available at **www.mhhe.com/forouzan6e**. As students read through *Data Communications and Networking with TCP/IP Protocol Suite*, they can go online to take self-grading quizzes. They can also access lecture materials such as PowerPoint slides and get additional review from animated figures from the book. Selected solutions are also available over the Web. The solutions to odd-numbered problems are provided to students, and instructors can use a password to access the complete set of solutions.

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Behrouz A. Forouzan
Los Angeles, CA
January 2021

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CHAPTER 1

Introduction

Data communications and networking have changed the way we do business and the way we live. The largest computer network, the Internet, has billions of users in the world who use wired and wireless transmission media to connect small and large computers.

Data communications and networking are not only used in business and personal communication but have found many political and social applications. People are able how to communicate with others all over the world to express their social and political opinions and problems. Communities are not isolated any more.

But before we ask how quickly we can get hooked up, we need to know how networks operate, what types of technologies are available, and which design best fills which set of needs.

This chapter paves the way for the rest of the book. It is divided into six sections.

- The first section introduces data communications and defines its components and the types of data exchanged.
- The second section introduces networks and defines their criteria and structures.
- The third section discusses different types of networks: LANs, WANs, and internetworks (internets). It also introduces the Internet, the largest internet in the world.

- The fourth section introduces protocol layering and its principles.
- The fifth section introduces the TCP/IP protocol suite and gives a brief description of each layer.
- The sixth section gives a brief historical description of the OSI model and compares it with the TCP/IP protocol suite.

1.1 DATA COMMUNICATIONS

When we communicate, we are sharing information or data. This sharing can be local or remote. Local communication usually occurs face to face, while remote communication takes place over a distance. The word ***data*** refers to information presented in whatever form is agreed upon by the parties creating and using it.

Data communications is the exchange of data between two devices via some form of transmission medium such as a wire cable. For data communications to occur, the communicating devices must be part of a communications system made up of a combination of hardware (physical equipment) and software (programs). The effectiveness of a data communications system depends on four fundamental characteristics: delivery, accuracy, timeliness, and jitter.

1. **Delivery.** The system must deliver data to the correct destination. Data must be received by the intended device or user and only by that device or user.
2. **Accuracy.** The system must deliver the data accurately. Data that have been altered in transmission and left uncorrected are unusable.
3. **Timeliness.** The system must deliver data in a timely manner. Data delivered late are useless. In the case of video and audio, timely delivery

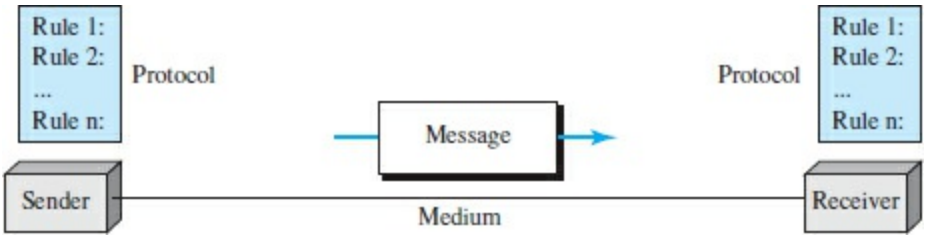
means delivering data as they are produced, in the same order that they are produced, and without significant delay. This kind of delivery is called *real-time* transmission.

4. **Jitter.** Jitter refers to the variation in the packet arrival time. It is the uneven delay in the delivery of audio or video packets. For example, let us assume that video packets are sent every 30 ms. If some of the packets arrive with a 30-ms delay and others with a 40-ms delay, the video will have an uneven quality.

1.1.1 Components

A data communications system has five components (see Figure 1.1).

Figure 1.1 *Five components of a data communications system*



1. **Message.** The **message** is the information (data) to be communicated. Popular forms of information include text, numbers, pictures, audio, and video.
2. **Sender.** The **sender** is the device that sends the data message. It can be a computer, a telephone handset, a video camera, and so on.
3. **Receiver.** The **receiver** is the device that receives the message. It can be a computer, workstation, telephone handset, television, and so on.
4. **Transmission medium.** The **transmission medium** is the physical path by which a message travels from sender to receiver. Some examples of transmission media include twisted-pair wire, coaxial cable, fiber-optic

cable, and radio waves.

5. **Protocol.** A **protocol** is a set of rules that govern data communications. It represents an agreement between the communicating devices. Without a protocol, two devices may be connected but not able to communicate, just as a person speaking French cannot be understood by a person who speaks only Japanese.

1.1.2 Message

Information today comes in different forms such as text, numbers, images, audio, and video.

Text

In data communications, text is represented as a bit pattern, a sequence of bits (0s or 1s). Different sets of bit patterns have been designed to represent text symbols. Each set is called a **code**, and the process of representing symbols is coding. Today, the prevalent coding system is **Unicode**, which uses 32 bits to represent a symbol or character used in any language in the world (see Appendix A).

Numbers

Numbers are also represented by bit patterns. However, a code such as Unicode is not used to represent numbers; a number is directly converted to a binary number to simplify mathematical operations (see Appendix B).

Images

Images are also represented by bit patterns. In its simplest form, an image is composed of a matrix of pixels (picture elements), where each pixel is a small dot. The number of pixels depends on the *resolution.* For example, an image can be divided into 1000 pixels or 10,000 pixels. In the second case, there is a better representation of the image (better resolution), but more memory is needed to store the image.

After an image is divided into pixels, each pixel is assigned a bit pattern. The size and the value of the pattern depend on the image. For an image

made up of only black and white dots (e.g., a chessboard), a 1-bit pattern is enough to represent a pixel.

If an image is not made up of pure white and pure black pixels, you can increase the size of the bit pattern to include the gray scale. For example, to show four levels of gray scale, you can use 2-bit patterns. A black pixel can be represented by 00, a dark gray pixel by 01, a light gray pixel by 10, and a white pixel by 11.

There are several methods to represent color images. One method is called **RGB**, so called because each color is made up of a combination of three primary colors: *r*ed, *g*reen, and *b*lue. The intensity of each color is measured, and a bit pattern is assigned to it. Another method is called **YCM**, in which a color is made up of a combination of three other primary colors: *y*ellow, cyan, and magenta.

Audio

Audio refers to the recording or broadcasting of sound or music. Audio is by nature different from text, numbers, or images. It is continuous, not discrete. Even when we use a microphone to change voice or music to an electric signal, we create a continuous signal. Later in the book we learn how to change sound or music to a digital or an analog signal.

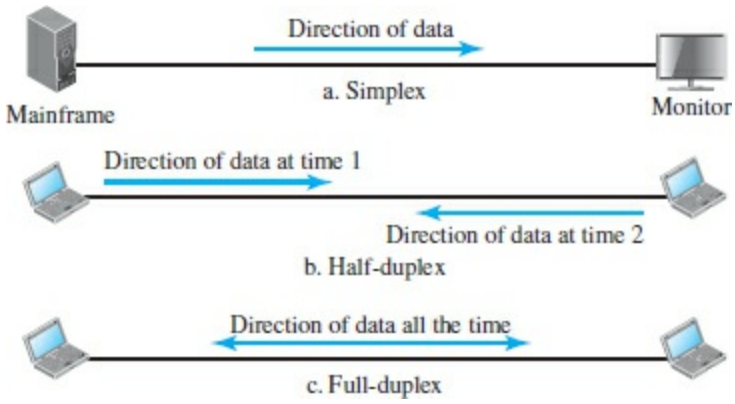
Video

Video refers to the recording or broadcasting of a picture or movie. Video can either be produced as a continuous entity (e.g., by a TV camera), or it can be a combination of images, each a discrete entity, arranged to convey the idea of motion.

1.1.3 Data Flow

Communication between two devices can be simplex, half-duplex, or full-duplex as shown in Figure 1.2.

Figure 1.2 *Data flow (simplex, half-duplex, and full-duplex)*



Simplex

In **simplex mode**, the communication is unidirectional, as on a one-way street. Only one of the two devices on a link can transmit; the other can only receive (see Figure 1.2a). Keyboards and traditional monitors are examples of simplex devices. The keyboard can only introduce input; the monitor can only accept output.

Half-Duplex

In **half-duplex mode**, each station can both transmit and receive, but not at the same time. When one device is sending, the other can only receive, and vice versa (see Figure 1.2b). Walkie-talkies and CB (citizens band) radios are both half-duplex systems.

Full-Duplex

In **full-duplex mode**, both stations can transmit and receive simultaneously (see Figure 1.2c). The full-duplex mode is like a two-way street with traffic flowing in both directions at the same time. In full-duplex mode, signals going in one direction share the capacity of the link with signals going in the other direction. One common example of full-duplex communication is the telephone network. When two people are communicating by a telephone line, both can talk and listen at the same time.

1.2 NETWORKS

A **network** is the interconnection of a set of devices capable of communication. In this definition, a device can be a **host**, such as a large computer, desktop, laptop, workstation, cellular phone, or security system. A device in this definition can also be a **connecting device** such as a router that connects the network to other networks, a switch that connects devices together, or a modem (modulator-demodulator) that changes the form of data.

1.2.1 Network Criteria

A network must be able to meet a certain number of criteria. The most important of these are ***performance***, ***reliability***, and ***security***.

Performance

Performance can be measured in many ways, including transit time and response time. Transit time is the amount of time required for a message to travel from one device to another. Response time is the elapsed time between an inquiry and a response. The performance of a network depends on a number of factors, including the number of users, the type of transmission medium, the capabilities of the connected hardware, and the efficiency of the software.

Reliability

In addition to accuracy of delivery, network **reliability** is measured by the frequency of failure, the time it takes a link to recover from a failure, and the network's robustness in a catastrophe.

Security

Network **security** issues include protecting data from unauthorized access, protecting data from damage and development, and implementing policies and procedures for recovery from breaches and data losses.

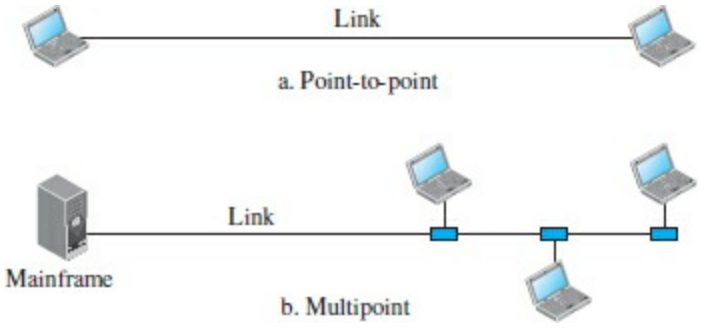
1.2.2 Physical Structures

Before discussing networks, we need to define some network attributes.

Type of Connection

A network is two or more devices connected through links. A link is a communications pathway that transfers data from one device to another. For communication to occur, two devices must be connected in some way to the same link at the same time. There are two possible types of connections: *point-to-point* and *multipoint* (see Figure 1.3 on next page).

Figure 1.3 *Types of connections: point-to-point and multipoint*



Point-to-Point

A **point-to-point connection** provides a dedicated link between two devices. The entire capacity of the link is reserved for transmission between those two devices.

Multipoint

A **multipoint** (also called **multidrop**) **connection** is one in which more than two devices share a single link. In a multipoint environment, the capacity of the channel is shared, either spatially or temporally. If several devices can use the link simultaneously, it is a *spatially shared* connection. If users must take turns, it is a *timeshared* connection.

Physical Topology

The term ***physical topology*** refers to the way in which a network is laid out physically. Two or more devices connect to a link; two or more links form a topology. The topology of a network is the geometric representation of the relationship of all the links and linking devices (usually called **nodes**) to one another. There are four basic topologies possible: *mesh*, *star*, *bus*, and *ring*.

Mesh Topology

In a **mesh topology**, every device has a dedicated point-to-point link to every other device. The term *dedicated* means that the link carries traffic only between the two devices it connects. To find the number of physical links in a fully connected mesh network with n nodes, we first consider that each node must be connected to every other node. Node 1 must be connected to $n - 1$ nodes, node 2 must be connected to $n - 1$ nodes, and finally node n must be connected to $n - 1$ nodes. We need $n(n - 1)$ physical links. To accommodate that many links, every device on the network must have $n - 1$ input/output (I/O) ports (see Figure 1.4 on next page) to be connected to the other $n - 1$ stations.

Star Topology

In a **star topology**, each device has a dedicated point-to-point link only to a central controller, usually called a **hub**. The devices are not directly linked to one another. Unlike a mesh topology, a star topology does not allow direct traffic between devices. The controller acts as an exchange: If one device wants to send data to another, it sends the data to the controller, which then relays the data to the other connected device (see Figure 1.5).

Figure 1.4 *A fully connected mesh topology (five devices)*

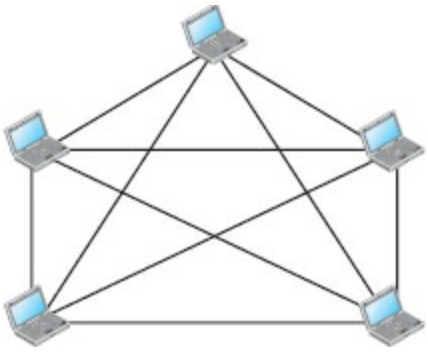
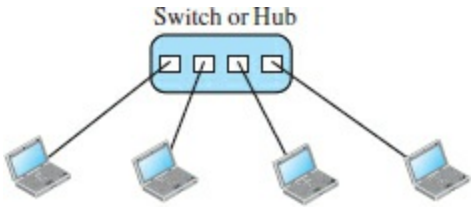


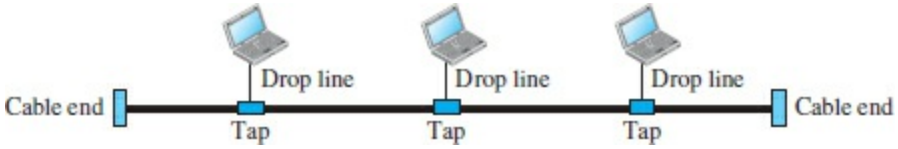
Figure 1.5 *A star topology connecting four stations*



Bus Topology

The preceding topology examples all describe point-to-point connections. A **bus topology**, on the other hand, is multipoint. One long cable acts as a **backbone** to link all the devices in a network (see Figure 1.6).

Figure 1.6 *A bus topology connecting three stations*

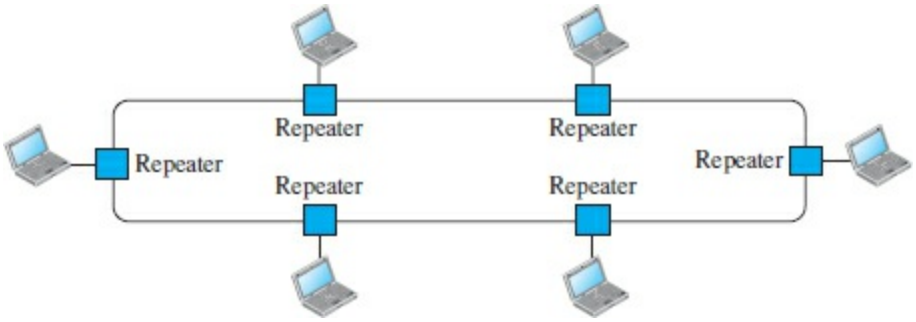


Nodes are connected to the bus cable by drop lines and taps. A *drop line* is a connection running between the device and the main cable. A *tap* is a connector that either splices into the main cable or punctures the sheathing of a cable to create a contact with the metallic core.

Ring Topology

In a **ring topology**, each device has a dedicated point-to-point connection with only the two devices on either side of it. A signal is passed along the ring in one direction, from device to device, until it reaches its destination. Each device in the ring incorporates a repeater, which regenerates the bits and passes them along (see Figure 1.7).

Figure 1.7 *A ring topology connecting six stations*



1.3 NETWORK TYPES

Now we discuss different types of networks: LANs and WANs.

1.3.1 Local Area Network

A **local area network (LAN)** is usually privately owned and connects some hosts in a single office, building, or campus.

Each host in a LAN has an identifier, which is an address that uniquely defines the host in the LAN. A packet sent by a host to another host carries both the source host's and the destination host's addresses.

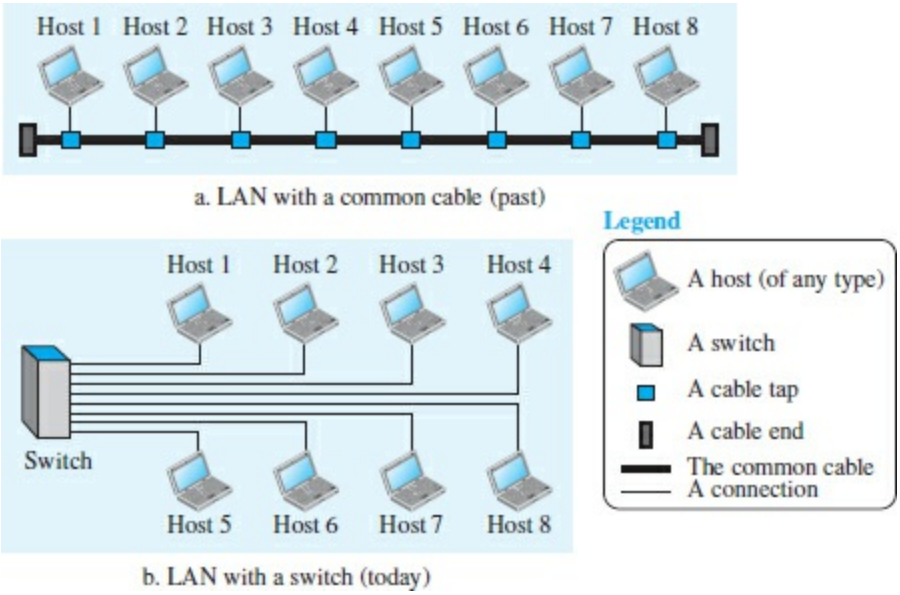
When LANs were used in isolation (which is rare today), they were designed to allow resources to be shared between the hosts. As we will see shortly, LANs today are connected to each other and to WANs (discussed

next) to create communication at a wider level (see Figure 1.8 on next page).

1.3.2 Wide Area Network (WAN)

A **wide area network (WAN)** is also an interconnection of devices capable of communication. However, there are some differences between a LAN and a WAN. A LAN is normally limited in size, spanning an office, a building, or a campus; a WAN has a wider geographical span, spanning a town, a state, a country, or even the world. A LAN interconnects hosts; a WAN interconnects connecting devices such as switches, routers, or modems. We see two distinct examples of WANs today: point-to-point WANs and switched WANs.

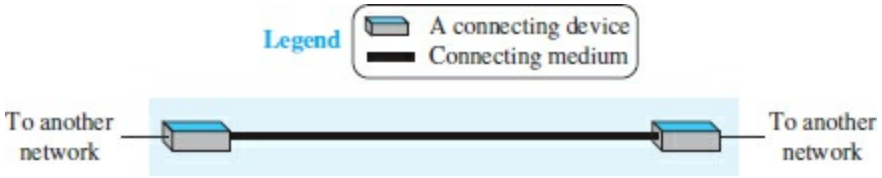
Figure 1.8 *An isolated LAN in the past and today*



Point-to-Point WAN

A point-to-point WAN is a network that connects two communicating devices through a transmission medium (cable or air). Figure 1.9 shows an example of a point-to-point WAN.

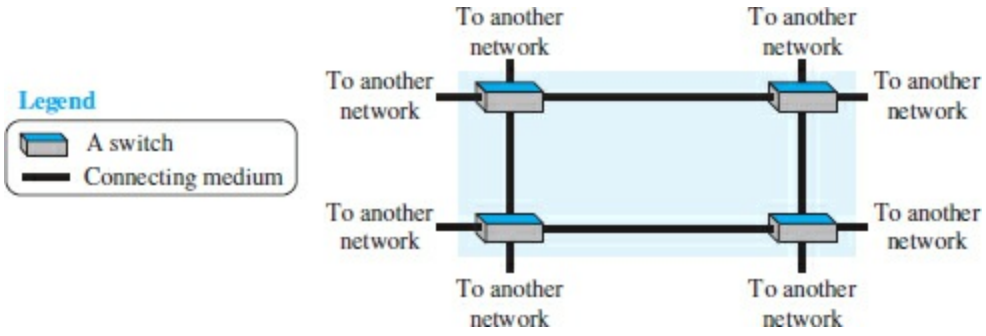
Figure 1.9 *A point-to-point WAN*



Switched WAN

A switched WAN is a network with more than two ends. It is used in the backbone of a global communications network today. Figure 1.10 shows an example of a switched WAN.

Figure 1.10 *A switched WAN*



Internetwork

Today, it is very rare to see a LAN or a WAN in isolation; they are connected to one another. When two or more networks are connected, they make an **internetwork**, or *internet*. As an example, assume that an organization has two offices, one on the east coast and the other on the west coast. Each office has a LAN that allows all employees in the office to communicate with each other. To make the communication between employees at different offices possible, the management leases a point-to-point dedicated WAN from a service provider, such as a telephone company, and connects the two LANs.

Now the company has an internetwork, or a private internet (with lowercase *i*). Communication between offices is now possible. Figure 1.11 shows this internet.

Figure 1.11 *An internetwork made of two LANs and one point-to-point WAN*

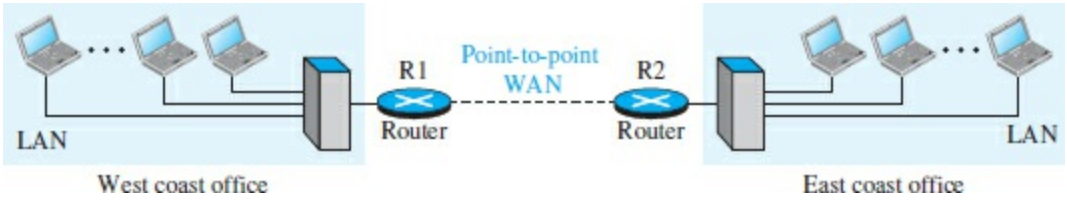


Figure 1.12 shows another internet with several LANs and WANs connected. One of the WANs is a switched WAN with four switches.

1.3.3 The Internet

As we discussed before, an *internet* (note the lowercase *i*) is two or more networks that can communicate with each other. The most notable internet is called the **Internet** (uppercase *I*) and is composed of thousands of interconnected networks. Figure 1.13 shows a conceptual (not geographical) view of the Internet.

Figure 1.12 *A heterogeneous internetwork made of four WANs and two LANs*

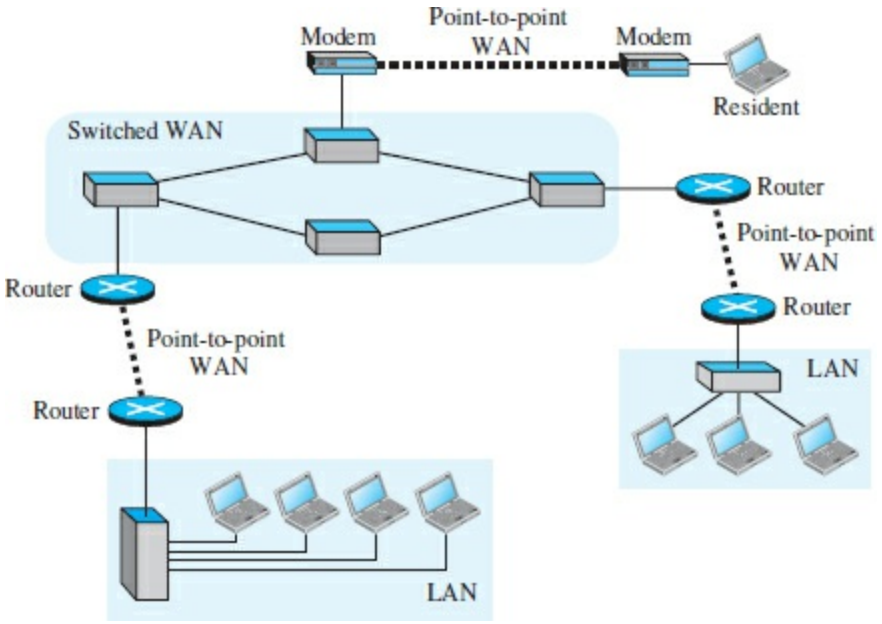
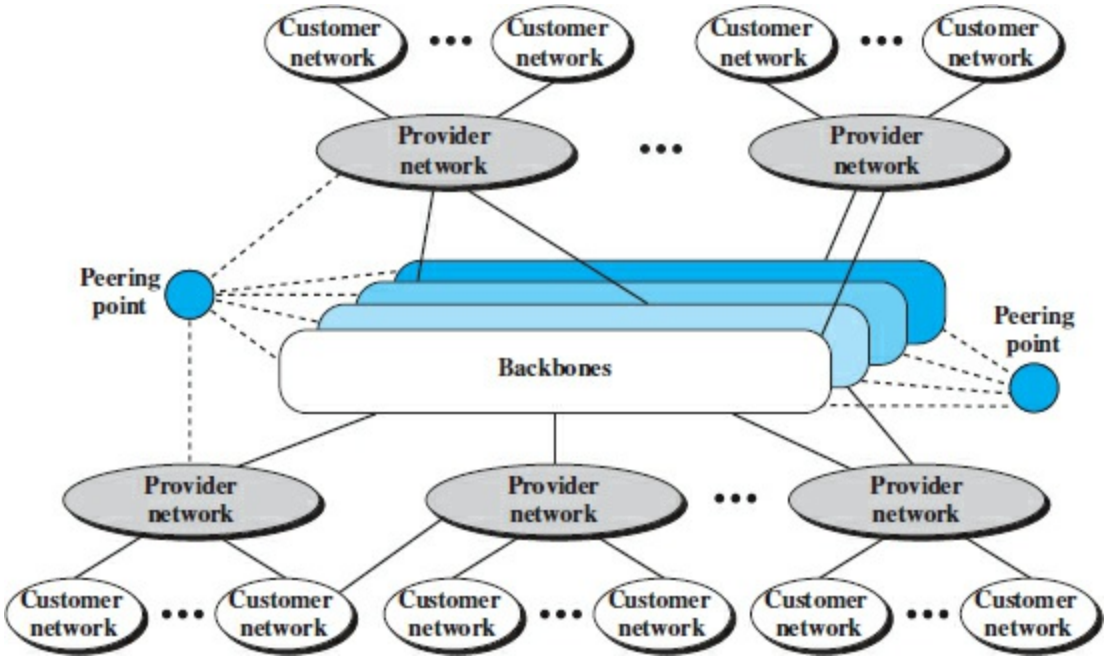


Figure 1.13 *The Internet today*



The figure shows the Internet as several backbones, provider networks,

and customer networks. At the top level, the *backbones* are large networks owned by some communication companies. The backbone networks are connected through some complex switching systems, called *peering points*. At the second level, there are smaller networks, called *provider networks*, that use the services of the backbones for a fee. The provider networks are connected to backbones and sometimes to other provider networks. The *customer networks* are networks at the edge of the Internet that actually use the services provided by the Internet. They pay fees to provider networks for receiving services.

Backbones and provider networks are also called **Internet Service Providers (ISPs)**. The backbones are often referred to as international ISPs; the provider networks are often referred to as national or regional ISPs.

1.3.4 Accessing the Internet

The Internet today is an internetwork that allows any user to become part of it. The user, however, needs to be physically connected to an ISP. The physical connection is normally done through a point-to-point WAN (such as a telephone network, a cable network, a wireless network, or other types of networks).

Using Telephone Networks

Today most residences and small businesses have telephone service, which means they are connected to a telephone network. Because most telephone networks have already connected themselves to the Internet, one option for residences and small businesses to connect to the Internet is to change the voice line between the residence or business and the telephone center to a point-to-point WAN. This can be done in two ways.

- ***Dial-up service.*** The first solution is to add a modem that converts data to voice to the telephone line. The software installed on the computer dials the ISP and imitates making a telephone connection. Unfortunately, the dial-up service is very slow, and when the line is used for an Internet connection, it cannot be used for a telephone (voice) connection. It is only useful for small residences and businesses with occasional connection to the Internet.

- ***DSL Service***. Since the advent of the Internet, some telephone companies have upgraded their telephone lines to provide higher-speed Internet services to residences or small businesses. The digital subscriber line (DSL) service also allows the line to be used simultaneously for voice and data communications.

Using Cable Networks

More and more residents over the last two decades have begun using cable TV services instead of antennas to receive TV broadcasting. The cable companies have been upgrading their cable networks and connecting to the Internet. A residence or a small business can be connected to the Internet by using this service. It provides a higher-speed connection, but the speed varies depending on the number of neighbors that use the same cable.

Using Wireless Networks

Wireless connectivity has recently become increasingly popular. A household or a small business can use a combination of wireless and wired connections to access the Internet. With the growing wireless WAN access, a household or a small business can be connected to the Internet through a wireless WAN.

Direct Connection to the Internet

A large organization or a large corporation can itself become a local ISP and be connected to the Internet. This can be done if the organization or the corporation leases a high-speed WAN from a carrier provider and connects itself to a regional ISP. For example, a large university with several campuses can create an internetwork and then connect the internetwork to the Internet.

1.4 PROTOCOL LAYERING

We defined the term *protocol* before. In data communications and networking, a protocol defines the rules that both the sender and receiver and