

INTERNATIONAL
EDITION



Data and Computer Communications

TENTH EDITION

William Stallings



ALWAYS LEARNING

PEARSON

DATA AND COMPUTER COMMUNICATIONS

Tenth Edition

William Stallings

International Edition contributions by

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PEARSON

For Tricia

CONTENTS

Preface 13

Acknowledgments 21

About the Author 23

Chapter 0 Guide for Readers and Instructors 25

- 0.1 Outline of the Book 26
- 0.2 A Roadmap for Readers and Instructors 27
- 0.3 Internet and Web Resources 28
- 0.4 Standards 29

UNIT ONE FUNDAMENTALS 31

PART ONE OVERVIEW 32

Chapter 1 Data Communications, Data Networks, and the Internet 32

- 1.1 Data Communications and Networking for Today's Enterprise 33
- 1.2 A Communications Model 39
- 1.3 Data Communications 42
- 1.4 Networks 45
- 1.5 The Internet 48
- 1.6 An Example Configuration 53

Chapter 2 Protocol Architecture, TCP/IP, and Internet-Based Applications 55

- 2.1 The Need for a Protocol Architecture 56
 - 2.2 A Simple Protocol Architecture 57
 - 2.3 The TCP/IP Protocol Architecture 61
 - 2.4 Standardization within a Protocol Architecture 69
 - 2.5 Traditional Internet-Based Applications 72
 - 2.6 Multimedia 72
 - 2.7 Sockets Programming 76
 - 2.8 Recommended Reading and Animation 85
 - 2.9 Key Terms, Review Questions, and Problems 87
 - 2.10 Sockets Programming Assignments 90
- Appendix 2A The Trivial File Transfer Protocol 90

PART TWO DATA COMMUNICATIONS 95

Chapter 3 Data Transmission 95

- 3.1 Concepts and Terminology 96
 - 3.2 Analog and Digital Data Transmission 108
 - 3.3 Transmission Impairments 116
 - 3.4 Channel Capacity 122
 - 3.5 Recommended Reading 128
 - 3.6 Key Terms, Review Questions, and Problems 128
- Appendix 3A Decibels and Signal Strength 131

6 CONTENTS

Chapter 4	Transmission Media	134
4.1	Guided Transmission Media	136
4.2	Wireless Transmission	151
4.3	Wireless Propagation	159
4.4	Line-of-Sight Transmission	164
4.5	Recommended Reading	168
4.6	Key Terms, Review Questions, and Problems	169
Chapter 5	Signal Encoding Techniques	173
5.1	Digital Data, Digital Signals	175
5.2	Digital Data, Analog Signals	186
5.3	Analog Data, Digital Signals	197
5.4	Recommended Reading and Animations	204
5.5	Key Terms, Review Questions, and Problems	205
Chapter 6	Error Detection and Correction	210
6.1	Types of Errors	212
6.2	Error Detection	213
6.3	Parity Check	214
6.4	The Internet Checksum	216
6.5	Cyclic Redundancy Check (CRC)	218
6.6	Forward Error Correction	225
6.7	Recommended Reading and Animations	231
6.8	Key Terms, Review Questions, and Problems	232
Chapter 7	Data Link Control Protocols	235
7.1	Flow Control	237
7.2	Error Control	244
7.3	High-Level Data Link Control (HDLC)	250
7.4	Recommended Reading and Animations	257
7.5	Key Terms, Review Questions, and Problems	257
Chapter 8	Multiplexing	260
8.1	Frequency-Division Multiplexing	262
8.2	Synchronous Time-Division Multiplexing	268
8.3	Cable Modem	278
8.4	Asymmetric Digital Subscriber Line	279
8.5	xDSL	284
8.6	Multiple Channel Access	285
8.7	Recommended Reading and Animations	289
8.8	Key Terms, Review Questions, and Problems	290

PART THREE WIDE AREA NETWORKS 293

Chapter 9	WAN Technology and Protocols	293
9.1	Switched Communications Networks	295
9.2	Circuit-Switching Networks	296
9.3	Circuit-Switching Concepts	299
9.4	Softswitch Architecture	305

9.5	Packet-Switching Principles	307
9.6	Asynchronous Transfer Mode	316
9.7	Recommended Reading	321
9.8	Key Terms, Review Questions, and Problems	322
Chapter 10	Cellular Wireless Networks	326
10.1	Principles of Cellular Networks	327
10.2	Cellular Network Generations	340
10.3	LTE-Advanced	344
10.4	Recommended Reading	352
10.5	Key Terms, Review Questions, and Problems	353

PART FOUR LOCAL AREA NETWORKS 355

Chapter 11 Local Area Network Overview 355

11.1	Bus and Star Topologies	356
11.2	LAN Protocol Architecture	358
11.3	Bridges	366
11.4	Hubs and Switches	374
11.5	Virtual LANs	377
11.6	Recommended Reading and Animations	382
11.7	Key Terms, Review Questions, and Problems	383

Chapter 12 Ethernet 385

12.1	Traditional Ethernet	387
12.2	High-Speed Ethernet	395
12.3	IEEE 802.1Q VLAN Standard	405
12.4	Recommended Reading and Animations	407
12.5	Key Terms, Review Questions, and Problems	407
Appendix 12A	Digital Signal Encoding for LANs	409
Appendix 12B	Scrambling	416

Chapter 13 Wireless LANs 419

13.1	Overview	420
13.2	IEEE 802.11 Architecture and Services	424
13.3	IEEE 802.11 Medium Access Control	428
13.4	IEEE 802.11 Physical Layer	436
13.5	Gigabit Wi-Fi	443
13.6	IEEE 802.11 Security Considerations	446
13.7	Recommended Reading	447
13.8	Key Terms, Review Questions, and Problems	448

PART FIVE INTERNET AND TRANSPORT PROTOCOLS 451

Chapter 14 The Internet Protocol 451

14.1	Principles of Internetworking	452
14.2	Internet Protocol Operation	457
14.3	Internet Protocol	464
14.4	IPv6	474
14.5	Virtual Private Networks and IP Security	484

8 CONTENTS

- 14.6 Recommended Reading and Animations 487
- 14.7 Key Terms, Review Questions, and Problems 488

Chapter 15 Transport Protocols 491

- 15.1 Connection-Oriented Transport Protocol Mechanisms 492
- 15.2 TCP 511
- 15.3 UDP 518
- 15.4 Recommended Reading and Animations 519
- 15.5 Key Terms, Review Questions, and Problems 520

UNIT TWO ADVANCED TOPICS IN DATA COMMUNICATIONS AND NETWORKING 523

PART SIX DATA COMMUNICATIONS AND WIRELESS NETWORKS 524

Chapter 16 Advanced Data Communications Topics 524

- 16.1 Analog Data, Analog Signals 525
- 16.2 Forward Error-Correcting Codes 532
- 16.3 ARQ Performance Issues 547
- 16.4 Recommended Reading and Animations 554
- 16.5 Key Terms, Review Questions, and Problems 556

Chapter 17 Wireless Transmission Techniques 558

- 17.1 MIMO Antennas 559
- 17.2 OFDM, OFDMA, and SC-FDMA 562
- 17.3 Spread Spectrum 568
- 17.4 Direct Sequence Spread Spectrum 569
- 17.5 Code Division Multiple Access 574
- 17.6 Recommended Reading 577
- 17.7 Key Terms, Review Questions, and Problems 578

Chapter 18 Wireless Networks 582

- 18.1 Fixed Broadband Wireless Access 583
- 18.2 WiMAX/IEEE 802.16 585
- 18.3 Bluetooth Overview 597
- 18.4 Bluetooth Radio Specification 601
- 18.5 Bluetooth Baseband Specification 601
- 18.6 Bluetooth Logical Link Control and Adaptation Protocol 610
- 18.7 Recommended Reading 612
- 18.8 Key Terms, Review Questions, and Problems 612

PART SEVEN INTERNETWORKING 614

Chapter 19 Routing 614

- 19.1 Routing in Packet-Switching Networks 615
- 19.2 Examples: Routing in ARPANET 625
- 19.3 Internet Routing Protocols 631
- 19.4 Least-Cost Algorithms 642
- 19.5 Recommended Reading and Animations 648
- 19.6 Key Terms, Review Questions, and Problems 649

Chapter 20	Congestion Control	653
20.1	Effects of Congestion	655
20.2	Congestion Control	660
20.3	Traffic Management	662
20.4	Congestion Control in Packet-Switching Networks	667
20.5	TCP Congestion Control	667
20.6	Datagram Congestion Control Protocol	679
20.7	Recommended Reading and Animations	684
20.8	Key Terms, Review Questions, and Problems	685

Chapter 21	Internetwork Operation	690
21.1	Multicasting	691
21.2	Software-Defined Networks	703
21.3	OpenFlow	707
21.4	Mobile IP	714
21.5	Dynamic Host Configuration Protocol	725
21.6	Recommended Reading and Animations	727
21.7	Key Terms, Review Questions, and Problems	728

Chapter 22	Internetwork Quality of Service	732
22.1	QOS Architectural Framework	734
22.2	Integrated Services Architecture	737
22.3	Resource Reservation Protocol	744
22.4	Differentiated Services	755
22.5	Service Level Agreements	763
22.6	IP Performance Metrics	765
22.7	Recommended Reading and Web Sites	768
22.8	Key Terms, Review Questions, and Problems	770

Chapter 23	Multiprotocol Label Switching	773
23.1	The Role of MPLS	775
23.2	Background	777
23.3	MPLS Operation	779
23.4	Labels	784
23.5	FECs, LSPs, and Labels	787
23.6	Label Distribution	789
23.7	Traffic Engineering	794
23.8	Virtual Private Networks	798
23.9	Recommended Reading	801
23.10	Key Terms, Review Questions, and Problems	801

PART EIGHT INTERNET APPLICATIONS 803

Chapter 24	Electronic Mail, DNS, and HTTP	803
24.1	Electronic Mail—SMTP and MIME	804
24.2	Internet Directory Service: DNS	817
24.3	Web Access and HTTP	826
24.4	Recommended Reading and Animations	837
24.5	Key Terms, Review Questions, and Problems	838

10 CONTENTS

Chapter 25 Internet Multimedia Support 841

- 25.1 Real-Time Traffic 842
- 25.2 Voice Over IP 845
- 25.3 Session Initiation Protocol 848
- 25.4 Real-Time Transport Protocol (RTP) 852
- 25.5 Recommended Reading 862
- 25.6 Key Terms, Review Questions, and Problems 863

APPENDICES

Appendix A Fourier Analysis 864

- A.1 Fourier Series Representation of Periodic Signals 864
- A.2 Fourier Transform Representation of Aperiodic Signals 865
- A.3 Recommended Reading 868

Appendix B Projects and Other Student Exercises for Teaching Data and Computer Communications 869

- B.1 Animations and Animation Assignments 870
- B.2 Practical Exercises 870
- B.3 Sockets Projects 870
- B.4 Wireshark Projects 871
- B.5 Simulation and Modeling Projects 871
- B.6 Performance Modeling 872
- B.7 Research Projects 872
- B.8 Reading/Report Assignments 873
- B.9 Writing Assignments 873
- B.10 Discussion Topics 873

References 874

Index 887

ONLINE CHAPTERS AND APPENDICES¹ PART NINE NETWORK SECURITY

Chapter 26 Computer and Network Security Threats

- 26.1 Computer Security Concepts
- 26.2 Threats, Attacks, and Assets
- 26.3 Intruders
- 26.4 Malicious Software Overview
- 26.5 Viruses, Worms, and Bots
- 26.6 Recommended Reading
- 26.7 Key Terms, Review Questions, and Problems

Chapter 27 Computer and Network Security Techniques

- 27.1 Virtual Private Networks and IPsec
- 27.2 SSL and TLS

¹Online chapters and appendices are Premium Content, available via the access card at the front of this book.

27.3	Wi-Fi Protected Access
27.4	Intrusion Detection
27.5	Firewalls
27.6	Malware Defense
27.7	Recommended Reading
27.8	Key Terms, Review Questions, and Problems
Appendix C	Standards Organizations
Appendix D	Asynchronous and Synchronous Transmission
Appendix E	The OSI Model
Appendix F	The International Reference Alphabet
Appendix G	Proof of the Sampling Theorem
Appendix H	Ones Complement Representation and Addition
Appendix I	Statistical TDM
Appendix J	The Spanning Tree Algorithm
Appendix K	LAN Performance Issues
Appendix L	Matrix Multiplication and Determinants
Appendix M	Queuing Effects
Appendix N	Orthogonality, Correlation, and Autocorrelation
Appendix O	TCP/IP Example
Appendix P	Queue Management and Queueing Discipline
Appendix Q	Cryptographic Algorithms
Appendix R	Uniform Resource Locators (URLs) and Uniform Resource Identifiers (URIs)
Appendix S	Augmented Backus-Naur Form
Appendix T	Derivations of Equations and Examples
	Glossary

PREFACE

WHAT'S NEW IN THE TENTH EDITION

Since the ninth edition of this book went to press, the pace of change in this field continues unabated. In this new edition, I try to capture these changes while maintaining a broad and comprehensive coverage of the entire field. To begin the process of revision, the ninth edition of this book was extensively reviewed by a number of professors who teach the subject and by professionals working in the field. The result is that, in many places, the narrative has been clarified and tightened, and illustrations have been improved.

Beyond these refinements to improve pedagogy and user friendliness, there have been major substantive changes throughout the book. The chapter organization has been changed somewhat so that now the material is organized into two Units, with Unit Two containing more advanced material and an expansion of the material related to the Internet. Beyond this organizational revision, the most noteworthy changes include the following:

- **Sockets programming:** A new section introduces sockets programming. Plus a number of sockets programming assignments, with sample solutions, are available for instructors.
- **Software-defined networks:** A new section covers this widely used technology.
- **Wireless transmission technology:** The book provides a unified treatment of important transmission technologies for wireless networks, including FDD, TDD, FDMA, TDMA, CDMA, OFDM, OFDMA, SC-FDMA, and MIMO.
- **4G cellular networks:** A new section covers 4G networks and the LTE-Advanced specification.
- **Gigabit Wi-Fi:** A new section covers the two new Wi-Fi standards, IEEE 802.11ac and 802.11ad, which provide Wi-Fi in the Gbps range.
- **Fixed broadband wireless access:** New sections cover fixed broadband wireless access to the Internet and the related WiMAX standard.
- **Forward error correction:** Forward error correction techniques are essential in wireless networks. This new edition contains substantially expanded coverage of this important topic.
- **Personal area networks:** New sections cover personal area networks and the Bluetooth standard.
- **Dynamic Host Configuration Protocol (DHCP):** DHCP is a widely used protocol that enables dynamic IP address assignment. A new section covers this protocol.
- **Datagram Congestion Control Protocol:** DCCP is a new protocol that meets the needs of multimedia applications for a congestion control transport protocol without the overhead of TCP. A new section covers DCCP.

- **Protocol Independent Multicast (PIM):** PIM, the most important Internet multicast routing algorithm, is covered in a new section.
- **Quality of service (QoS) architectural framework:** A new section covers ITU-T Recommendation Y.1291, which provides an overall framework for provision of Internet QoS facilities.
- **Electronic mail:** The section on e-mail in Chapter 24 has been expanded to include a discussion of the standard Internet mail architecture.
- **Animations:** As a powerful aid to understanding the material, over 150 online animations are provided covering a wide range of topics from the book. An icon at the beginning of many chapters indicates that supporting animations are available to enhance the student's understanding.
- **Learning objectives:** Each chapter now begins with a list of learning objectives.
- **Sample syllabus:** The text contains more material than can be conveniently covered in one semester. Accordingly, instructors are provided with several sample syllabi that guide the use of the text within limited time (e.g., 16 weeks or 12 weeks). These samples are based on real-world experience by professors with the ninth edition.

In addition, the material that carries over from the ninth edition has been revised, with new figures and revised and updated content.

OBJECTIVES

This book attempts to provide a unified overview of the broad field of data and computer communications. The organization of the book reflects an attempt to break this massive subject into comprehensible parts and to build, piece by piece, a survey of the state of the art. The book emphasizes basic principles and topics of fundamental importance concerning the technology and architecture of this field and provides a detailed discussion of leading-edge topics.

The following basic themes serve to unify the discussion:

- **Principles:** Although the scope of this book is broad, there are a number of basic principles that appear repeatedly as themes and that unify this field. Examples are multiplexing, flow control, and error control. The book highlights these principles and contrasts their application in specific areas of technology.
- **Design approaches:** The book examines alternative approaches to meeting specific communication requirements.
- **Standards:** Standards have come to assume an increasingly important, indeed dominant, role in this field. An understanding of the current status and future direction of technology requires a comprehensive discussion of the related standards.

SUPPORT OF ACM/IEEE COMPUTER SCIENCE CURRICULA 2013

The book is intended for both an academic and a professional audience. For the professional interested in this field, the book serves as a basic reference volume and is suitable for self-study. As a textbook, it can be used for a one-semester or two-semester course. This edition is designed to support the recommendations of the current (February 2013) draft version of the ACM/IEEE Computer Science Curricula 2013 (CS2013). The CS2013 curriculum recommendation includes Networking and Communication (NC) as one of the Knowledge Areas in the Computer Science Body of Knowledge. CS2013 divides all course work into three categories: Core-Tier 1 (all topics should be included in the curriculum), Core-Tier-2 (all or almost all topics should be included), and elective (desirable to provide breadth and depth). In the NC area, CS2013 includes two Tier 1 topics and five Tier 2 topics, each of which has a number of subtopics. This text covers all of the topics and subtopics listed by CS2013 in these two tiers.

Table P.1 shows the support for the NC Knowledge Area provided in this textbook.

Table P.1 Coverage of CS2013 Networking and Communication (NC) Knowledge Area

Topic	Chapter Coverage
<p>Introduction (Tier 1)</p> <ul style="list-style-type: none"> – Organization of the Internet (Internet Service Providers, Content Providers, etc.) – Switching techniques (Circuit, packet, etc.) – Physical pieces of a network (hosts, routers, switches, ISPs, wireless, LAN, access point, firewalls, etc.) – Layering principles (encapsulation, multiplexing) – Roles of the different layers (application, transport, network, datalink, physical) 	<p>1-Data Communications 2-Protocol Architecture 9-WAN Technology</p>
<p>Networked Applications (Tier 1)</p> <ul style="list-style-type: none"> – Naming and address schemes (DNS, IP addresses, Uniform Resource Identifiers, etc.) – Distributed applications (client/server, peer-to-peer, cloud, etc.) – HTTP as an application layer protocol – Multiplexing with TCP and UDP – Socket APIs 	<p>24-Electronic mail, DNS, HTTP 2-Protocol Architecture</p>
<p>Reliable Data Delivery (Tier 2)</p> <ul style="list-style-type: none"> – Error control (retransmission techniques, timers) – Flow control (acknowledgments, sliding window) – Performance issues (pipelining) – TCP 	<p>6-Error Detection and Correction 7-Data Link Control 15-Transport Protocols</p>

Table P.1 Continued

Topic	Chapter Coverage
Routing And Forwarding (Tier 2) –Routing versus forwarding –Static routing –Internet Protocol (IP) –Scalability issues (hierarchical addressing)	19-Routing 14-The Internet Protocol
Local Area Networks (Tier 2) –Multiple Access Problem –Common approaches to multiple access (exponential-backoff, time division multiplexing, etc.) –Local Area Networks –Ethernet –Switching	11-Local Area Network Overview 12-Ethernet
Resource Allocation (Tier 2) –Need for resource allocation –Fixed allocation (TDM, FDM, WDM) versus dynamic allocation –End-to-end versus network-assisted approaches –Fairness –Principles of congestion control –Approaches to Congestion (Content Distribution Networks, etc.)	8-Multiplexing 20-Congestion Control 21-Internetwork QoS
Mobility (Tier 2) –Principles of cellular networks –802.11 networks –Issues in supporting mobile nodes (home agents)	10-Cellular Wireless Networks 13-Wireless LANs

PLAN OF THE TEXT

The book is divided into two units, comprising nine parts, which are described in Chapter 0:

- Unit One: Fundamentals of Data Communications and Networking
 - Overview
 - Data Communications
 - Wide Area Networks
 - Local Area Networks
 - Internet and Transport Layers
- Unit Two: Advanced Topics in Data Communications and Networking
 - Data Communications and Wireless Networks
 - Internetworking
 - Internet Applications
 - Network Security

The book includes a number of pedagogic features, including the use of animations and numerous figures and tables to clarify the discussions. Each chapter includes a list of key words, review questions, homework problems, and suggestions for further reading. The book also includes an extensive online glossary, a list of frequently used acronyms, and a reference list. In addition, a test bank is available to instructors.

The chapters and parts of the book are sufficiently modular to provide a great deal of flexibility in the design of courses. See Chapter 0 for a number of detailed suggestions for both top-down and bottom-up course strategies.

INSTRUCTOR SUPPORT MATERIALS

The major goal of this text is to make it as effective a teaching tool for this exciting and fast-moving subject as possible. This goal is reflected both in the structure of the book and in the supporting material. The text is accompanied by the following supplementary material to aid the instructor:

- **Solutions manual:** Solutions to all end-of-chapter Review Questions and Problems.
- **Projects manual:** Suggested project assignments for all of the project categories in the next section.
- **PowerPoint slides:** A set of slides covering all chapters, suitable for use in lecturing.
- **PDF files:** Reproductions of all figures and tables from the book.
- **Test bank:** A chapter-by-chapter set of questions with a separate file of answers.
- **Sample syllabuses:** The text contains more material than can be conveniently covered in one semester. Accordingly, instructors are provided with several sample syllabuses that guide the use of the text within limited time. These samples are based on real-world experience by professors with the ninth edition.

All of these support materials are available at the **Instructor Resource Center (IRC)** for this textbook, which can be reached through the publisher's Web site www.pearsoninternationaleditions.com/stallings or by clicking on the link labeled *Pearson Resources for Instructors* at this book's Companion Web site at WilliamStallings.com/DataComm. To gain access to the IRC, please contact your local Pearson sales representative.

The **Companion Web site**, at WilliamStallings.com/DataComm (click on *Instructor Resources* link), includes the following:

- Links to Web sites for other courses being taught using this book.
- Sign-up information for an Internet mailing list for instructors using this book to exchange information, suggestions, and questions with each other and with the author.

PROJECTS AND OTHER STUDENT EXERCISES

For many instructors, an important component of a data communications or networking course is a project or set of projects by which the student gets hands-on experience to reinforce concepts from the text. This book provides an unparalleled degree of support for including a projects component in the course. The IRC not only provides guidance on how to assign and structure the projects but also includes a set of User's Manuals for various project types plus specific assignments, all written especially for this book. Instructors can assign work in the following areas:

- **Animation assignments:** Described in the following section.
- **Practical exercises:** Using network commands, the student gains experience in network connectivity.
- **Sockets programming projects:** Described subsequently in this Preface.
- **Wireshark projects:** Wireshark is a protocol analyzer that enables students to study the behavior of protocols. A video tutorial is provided to get students started, in addition to a set of Wireshark assignments.
- **Simulation projects:** The student can use the simulation package *cnet* to analyze network behavior. The IRC includes a number of student assignments.
- **Performance modeling projects:** Two performance modeling techniques are introduced: a *tools* package and OPNET. The IRC includes a number of student assignments.
- **Research projects:** The IRC includes a list of suggested research projects that would involve Web and literature searches.
- **Reading/report assignments:** The IRC includes a list of papers that can be assigned for reading and writing a report, plus suggested assignment wording.
- **Writing assignments:** The IRC includes a list of writing assignments to facilitate learning the material.
- **Discussion topics:** These topics can be used in a classroom, chat room, or message board environment to explore certain areas in greater depth and to foster student collaboration.

This diverse set of projects and other student exercises enables the instructor to use the book as one component in a rich and varied learning experience and to tailor a course plan to meet the specific needs of the instructor and students. See Appendix B for details.

ANIMATIONS

Animations provide a powerful tool for understanding the complex mechanisms discussed in this book, including forward error correction, signal encoding, and protocols. Over 150 Web-based animations are used to illustrate many of the data communications and protocol concepts in this book. These animations are available online at the Premium Web site. For those chapters for which animations are available, this icon appears at the beginning of the chapter:



Twelve of the animations have been designed to allow for two types of assignments. First, the student can be given a specific set of steps to invoke and watch the animation, and then be asked to analyze and comment on the results. Second, the student can be given a specific end point and is required to devise a sequence of steps that achieve the desired result. The IRC includes a set of assignments for each of these animations, plus suggested solutions so that instructors can assess the student's work.

SOCKETS PROGRAMMING

Sockets are the fundamental element behind any kind of network communication using the TCP/IP protocol suite. Sockets programming is a relatively straightforward topic that can result in very satisfying and effective hands-on projects for students. This book provides considerable support to enable students to learn and use Sockets programming to enhance their understanding of networking, including:

1. Chapter 2 provides a basic introduction to Sockets programming and includes a detailed analysis of a TCP server and a TCP client program.
2. Chapter 2 also includes some end-of-chapter programming assignments using Sockets. Sample solutions are available at the IRC for this book.
3. Additional Sockets programming assignments, plus sample solutions, are available for instructors at the IRC. These include a number of moderate-size assignments and a more substantial project that, step by step, implements a simplified instant messaging client and server.
4. A different, additional set of Sockets assignments, plus sample solutions, are included in the supplemental homework problems available to students at the Premium Web site.

Taken together, these resources provide students with a solid understanding of Sockets programming and experience in developing networking applications.

ONLINE DOCUMENTS FOR STUDENTS

For this new edition, a substantial amount of original supporting material for students has been made available online, at two Web locations. The **Companion Web site**, at WilliamStallings.com/DataComm (click on *Student Resources* link), includes a list of relevant links organized by chapter and an errata sheet for the book.

Purchasing this textbook new also grants the reader six months of access to the **Premium Content site**, which includes the following materials:

- **Online chapters:** To limit the size and cost of the book, two chapters of the book, covering security, are provided in PDF format. The chapters are listed in this book's table of contents.
- **Online appendices:** There are numerous interesting topics that support material found in the text but whose inclusion is not warranted in the printed text.

A total of 18 online appendices cover these topics for the interested student. The appendices are listed in this book's table of contents.

- **Homework problems and solutions:** To aid the student in understanding the material, a separate set of homework problems with solutions is available.

To access the Premium Content site, click on the *Premium Content* link at the Companion Web site or at www.pearsoninternationaleditions.com/stallings and enter the student access code found on the card in the front of the book.

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Dr. William Stallings has authored 17 titles, and counting revised editions, over 40 books on computer security, computer networking, and computer architecture. His writings have appeared in numerous publications, including the *Proceedings of the IEEE*, *ACM Computing Reviews* and *Cryptologia*.

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In over 30 years in the field, he has been a technical contributor, technical manager, and an executive with several high-technology firms. He has designed and implemented both TCP/IP-based and OSI-based protocol suites on a variety of computers and operating systems, ranging from microcomputers to mainframes. As a consultant, he has advised government agencies, computer and software vendors, and major users on the design, selection, and use of networking software and products.

He created and maintains the *Computer Science Student Resource Site* at ComputerScienceStudent.com. This site provides documents and links on a variety of subjects of general interest to computer science students (and professionals). He is a member of the editorial board of *Cryptologia*, a scholarly journal devoted to all aspects of cryptology.

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GUIDE FOR READERS AND INSTRUCTORS

0.1 Outline of the Book

0.2 A Roadmap for Readers and Instructors

Course Emphasis
Bottom–Up versus Top–Down

0.3 Internet and Web Resources

Web Sites for This Book
Computer Science Student Resource Site
Other Web Sites

0.4 Standards

This book, with its accompanying Web support, covers a lot of material. Here, we give the reader some basic background information.

0.1 OUTLINE OF THE BOOK

The book is organized into two units. Unit One provides a survey of the fundamentals of data communications, networks, and Internet protocols. Unit Two covers more advanced or difficult topics in data communications and networks, and provides a more comprehensive discussion of Internet protocols and operation.

Unit One is organized into five parts:

Part One. Overview: Provides an introduction to the range of topics covered in the book. This part includes a general overview of data communications and networking, and a discussion of protocols and the TCP/IP protocol suite.

Part Two. Data Communications: Presents material concerned primarily with the exchange of data between two directly connected devices. Within this restricted scope, the key aspects of transmission, transmission media, error detection, link control, and multiplexing are examined.

Part Three. Wide Area Networks: Examines the technologies and protocols that have been developed to support voice, data, and multimedia communications over long-distance networks. The traditional technologies of packet switching and circuit switching, as well as the more contemporary ATM and cellular networks, are examined.

Part Four. Local Area Networks: Explores the technologies and architectures that have been developed for networking over shorter distances. The transmission media, topologies, and medium access control protocols that are the key ingredients of a LAN design are explored. This is followed by a detailed discussion of Ethernet and Wi-Fi networks.

Part Five. Internet and Transport Protocols: Discusses protocols at the Internet and Transport layers.

Unit Two consists of three parts:

Part Six. Data Communications and Wireless Networks: Treats important topics in these areas not covered in Unit One.

Part Seven. Internetworking: Examines a range of protocols and standards related to the operation of the Internet, including routing, congestion control, and quality of service.

Part Eight. Internet Applications: Looks at a range of applications that operate over the Internet.

In addition, there is an online **Part Nine. Security:** It covers security threats and techniques for countering these threats. A number of online appendices cover additional topics relevant to the book.

0.2 A ROADMAP FOR READERS AND INSTRUCTORS

The text contains more material than can be conveniently covered in one semester. Accordingly, the Instructor Resource Center (IRC) for this book includes several sample syllabi that guide the use of the text within limited time (e.g., 16 weeks or 12 weeks). Each alternative syllabus suggests a selection of chapters and a weekly schedule. These samples are based on real-world experience by professors with the previous edition.

The organization of the book into two units is intended to divide the material, roughly, into introductory and fundamental topics (Unit One) and advanced topics (Unit Two). Thus, a one-semester course could be limited to all or most of the material in Unit One.

In this section, we provide some other suggestions for organizing the material for a course.

Course Emphasis

The material in this book is organized into four broad categories: data transmission and communication, communications networks, network protocols, and applications and security. The chapters and parts of the book are sufficiently modular to provide a great deal of flexibility in the design of courses. The following are suggestions for three different course designs:

- **Fundamentals of Data Communications:** Parts One (overview), Two (data communications), and Three (wired WANs and cellular networks).
- **Communications Networks:** If the student has a basic background in data communications, then this course could cover Parts One (overview), Three (WAN), and Four (LAN).
- **Computer Networks:** If the student has a basic background in data communications, then this course could cover Part One (overview), Chapters 6 and 7 (error detection and correction, and data link control), Part Five (internet and transport protocols), and part or all of Parts Seven (internetworking) and Eight (applications).

In addition, a more streamlined course that covers the entire book is possible by eliminating certain chapters that are not essential on a first reading. The sample syllabi document at the IRC provides guidance on chapter selection.

Bottom-Up versus Top-Down

The book is organized in a modular fashion. After reading Part One, the other parts can be read in a number of possible sequences. Table 0.1a shows the bottom-up approach provided by reading the book from front to back. With this approach, each part builds on the material in the previous part, so that it is always clear how

Table 0.1 Suggested Reading Orders

(a) A bottom–up approach	(b) A shorter bottom–up approach
Part One: Overview	Part One: Overview
Part Two: Data Communications	Part Two: Data Communications (Chapters 3, 6, 7, 8)
Part Three: Wide Area Networks	Part Three: Wide Area Networks
Part Four: Local Area Networks	Part Four: Local Area Networks
Part Five: Internet and Transport Layers	Part Five: Internet and Transport Layers
Part Seven: Internetworking	
Part Eight: Internet Applications	
(c) A top–down approach	(d) A shorter top–down approach
Part One: Overview	Part One: Overview
Chapter 14: The Internet Protocol	Chapter 14: The Internet Protocol
Part Eight: Internet Applications	Part Eight: Internet Applications
Chapter 15: Transport Protocols	Chapter 15: Transport Protocols
Part Seven: Internetworking	Part Seven: Internetworking (Chapters 19, 20, 21)
Part Three: Wide Area Networks	Part Three: Wide Area Networks
Part Four: Local Area Networks	Part Four: Local Area Networks (Chapter 11)
Part Two: Data Communications	

a given layer of functionality is supported from below. There is more material than can be comfortably covered in a single semester, but the book’s organization makes it easy to eliminate some chapters and maintain the bottom–up sequence. Table 0.1b suggests one approach to a survey course.

Some readers, and some instructors, are more comfortable with a top–down approach. After the background material (Part One), the reader continues at the application level and works down through the protocol layers. This has the advantage of immediately focusing on the most visible part of the material, the applications, and then seeing, progressively, how each layer is supported by the next layer down. Table 0.1c is an example of a comprehensive treatment, and Table 0.1d is an example of a survey treatment.

0.3 INTERNET AND WEB RESOURCES

There are a number of resources available on the Internet and the Web that support this book and help readers keep up with developments in this field.

Web Sites for This Book

Three Web sites provide additional resources for students and instructors.

There is a **Companion Website** for this book at <http://williamstallings.com/DataComm>. For students, this Web site includes a list of relevant links, organized by chapter, and an errata list for the book. For instructors, this Web site provides

links to course pages by professors teaching from this book and provides a number of other useful documents and links.

There is also an access-controlled **Premium Content Website**, which provides a wealth of supporting material, including additional online chapters, additional online appendices, and a set of homework problems with solutions. See the card at the front of this book for access information.

Finally, additional material for instructors, including a solutions manual and a projects manual, is available at the **Instructor Resource Center (IRC)** for this book. See Preface for details and access information.

Computer Science Student Resource Site

I also maintain the **Computer Science Student Resource Site**, at ComputerScienceStudent.com. The purpose of this site is to provide documents, information, and links for computer science students and professionals. Links and documents are organized into seven categories:

- **Math:** Includes a basic math refresher, a queuing analysis primer, a number system primer, and links to numerous math sites.
- **How-to:** Advice and guidance for solving homework problems, writing technical reports, and preparing technical presentations.
- **Research resources:** Links to important collections of papers, technical reports, and bibliographies.
- **Other useful:** A variety of other useful documents and links.
- **Computer science careers:** Useful links and documents for those considering a career in computer science.
- **Writing help:** Help in becoming a clearer, more effective writer.
- **Miscellaneous topics and humor:** You have to take your mind off your work once in a while.

Other Web Sites

Numerous Web sites provide information related to the topics of this book. The Companion Website provides links to these sites, organized by chapter.

0.4 STANDARDS

Standards have come to play a dominant role in the information communications marketplace. Virtually all vendors of products and services are committed to supporting international standards. Throughout this book, we describe the most important standards in use or being developed for various aspects of data communications and networking. Various organizations have been involved in the development or promotion of these standards. The most important (in the current context) of these organizations are as follows:

- **Internet Society:** The Internet SOCIety (ISOC) is a professional membership society with worldwide organizational and individual membership. It provides

leadership in addressing issues that confront the future of the Internet and is the organization home for the groups responsible for Internet infrastructure standards, including the Internet Engineering Task Force (IETF) and the Internet Architecture Board (IAB). These organizations develop Internet standards and related specifications, all of which are published as Requests for Comments (RFCs).

- **IEEE 802:** The IEEE (Institute of Electrical and Electronics Engineers) 802 LAN/MAN Standards Committee develops local area network standards and metropolitan area network standards. The most widely used standards are for the Ethernet family, wireless LAN, bridging, and virtual bridged LANs. An individual working group provides the focus for each area.
- **ITU-T:** The International Telecommunication Union (ITU) is a United Nations agency in which governments and the private sector coordinate global telecom networks and services. The ITU Telecommunication Standardization Sector (ITU-T) is one of the three sectors of the ITU. ITU-T's mission is the production of standards covering all fields of telecommunications. ITU-T standards are referred to as Recommendations.
- **ISO:** The International Organization for Standardization (ISO)¹ is a worldwide federation of national standards bodies from more than 140 countries, one from each country. ISO is a nongovernmental organization that promotes the development of standardization and related activities with a view to facilitating the international exchange of goods and services, and to developing cooperation in the spheres of intellectual, scientific, technological, and economic activity. ISO's work results in international agreements that are published as International Standards.

A more detailed discussion of these organizations is contained in Appendix C.

¹ISO is not an acronym (in which case it would be IOS), but a word, derived from the Greek, meaning *equal*.