

Table of Contents

Chapter 1 Computer Networks and the Internet	1
1.1 What Is the Internet?	2
1.1.1 A Nuts-and-Bolts Description	2
1.1.2 A Services Description	5
1.1.3 What Is a Protocol?	7
1.2 The Network Edge	9
1.2.1 Access Networks	12
1.2.2 Physical Media	18
1.3 The Network Core	22
1.3.1 Packet Switching	22
1.3.2 Circuit Switching	27
1.3.3 A Network of Networks	32
1.4 Delay, Loss, and Throughput in Packet-Switched Networks	35
1.4.1 Overview of Delay in Packet-Switched Networks	35
1.4.2 Queuing Delay and Packet Loss	39
1.4.3 End-to-End Delay	42
1.4.4 Throughput in Computer Networks	44
1.5 Protocol Layers and Their Service Models	47
1.5.1 Layered Architecture	47
1.5.2 Encapsulation	53
1.6 Networks Under Attack	55
1.7 History of Computer Networking and the Internet	60
1.7.1 The Development of Packet Switching: 1961–1972	60
1.7.2 Proprietary Networks and Internetworking: 1972–1980	62
1.7.3 A Proliferation of Networks: 1980–1990	63
1.7.4 The Internet Explosion: The 1990s	64
1.7.5 The New Millennium	65
1.8 Summary	66
Homework Problems and Questions	68
Wireshark Lab	78
Interview: Leonard Kleinrock	80

Chapter 2 Application Layer	83
2.1 Principles of Network Applications	84
2.1.1 Network Application Architectures	86
2.1.2 Processes Communicating	88
2.1.3 Transport Services Available to Applications	91
2.1.4 Transport Services Provided by the Internet	93
2.1.5 Application-Layer Protocols	96
2.1.6 Network Applications Covered in This Book	97
2.2 The Web and HTTP	98
2.2.1 Overview of HTTP	98
2.2.2 Non-Persistent and Persistent Connections	100
2.2.3 HTTP Message Format	103
2.2.4 User-Server Interaction: Cookies	108
2.2.5 Web Caching	110
2.2.6 The Conditional GET	114
2.3 File Transfer: FTP	116
2.3.1 FTP Commands and Replies	118
2.4 Electronic Mail in the Internet	118
2.4.1 SMTP	121
2.4.2 Comparison with HTTP	124
2.4.3 Mail Message Format	125
2.4.4 Mail Access Protocols	125
2.5 DNS—The Internet’s Directory Service	130
2.5.1 Services Provided by DNS	131
2.5.2 Overview of How DNS Works	133
2.5.3 DNS Records and Messages	139
2.6 Peer-to-Peer Applications	144
2.6.1 P2P File Distribution	145
2.6.2 Distributed Hash Tables (DHTs)	151
2.7 Socket Programming: Creating Network Applications	156
2.7.1 Socket Programming with UDP	157
2.7.2 Socket Programming with TCP	163
2.8 Summary	168
Homework Problems and Questions	169
Socket Programming Assignments	179
Wireshark Labs: HTTP, DNS	181
Interview: Marc Andreessen	182

Chapter 3 Transport Layer 185

3.1	Introduction and Transport-Layer Services	186
3.1.1	Relationship Between Transport and Network Layers	186
3.1.2	Overview of the Transport Layer in the Internet	189
3.2	Multiplexing and Demultiplexing	191
3.3	Connectionless Transport: UDP	198
3.3.1	UDP Segment Structure	202
3.3.2	UDP Checksum	202
3.4	Principles of Reliable Data Transfer	204
3.4.1	Building a Reliable Data Transfer Protocol	206
3.4.2	Pipelined Reliable Data Transfer Protocols	215
3.4.3	Go-Back-N (GBN)	218
3.4.4	Selective Repeat (SR)	223
3.5	Connection-Oriented Transport: TCP	230
3.5.1	The TCP Connection	231
3.5.2	TCP Segment Structure	233
3.5.3	Round-Trip Time Estimation and Timeout	238
3.5.4	Reliable Data Transfer	242
3.5.5	Flow Control	250
3.5.6	TCP Connection Management	252
3.6	Principles of Congestion Control	259
3.6.1	The Causes and the Costs of Congestion	259
3.6.2	Approaches to Congestion Control	265
3.6.3	Network-Assisted Congestion-Control Example: ATM ABR Congestion Control	266
3.7	TCP Congestion Control	269
3.7.1	Fairness	279
3.8	Summary	283
	Homework Problems and Questions	285
	Programming Assignments	300
	Wireshark Labs: TCP, UDP	301
	Interview: Van Jacobson	302

Chapter 4 The Network Layer 305

4.1	Introduction	306
4.1.1	Forwarding and Routing	308
4.1.2	Network Service Models	310
4.2	Virtual Circuit and Datagram Networks	313
4.2.1	Virtual-Circuit Networks	314
4.2.2	Datagram Networks	317
4.2.3	Origins of VC and Datagram Networks	319

4.3	What's Inside a Router?	320
4.3.1	Input Processing	322
4.3.2	Switching	324
4.3.3	Output Processing	326
4.3.4	Where Does Queuing Occur?	327
4.3.5	The Routing Control Plane	331
4.4	The Internet Protocol (IP): Forwarding and Addressing in the Internet	331
4.4.1	Datagram Format	332
4.4.2	IPv4 Addressing	338
4.4.3	Internet Control Message Protocol (ICMP)	353
4.4.4	IPv6	356
4.4.5	A Brief Foray into IP Security	362
4.5	Routing Algorithms	363
4.5.1	The Link-State (LS) Routing Algorithm	366
4.5.2	The Distance-Vector (DV) Routing Algorithm	371
4.5.3	Hierarchical Routing	379
4.6	Routing in the Internet	383
4.6.1	Intra-AS Routing in the Internet: RIP	384
4.6.2	Intra-AS Routing in the Internet: OSPF	388
4.6.3	Inter-AS Routing: BGP	390
4.7	Broadcast and Multicast Routing	399
4.7.1	Broadcast Routing Algorithms	400
4.7.2	Multicast	405
4.8	Summary	412
	Homework Problems and Questions	413
	Programming Assignments	429
	Wireshark Labs: IP, ICMP	430
	Interview: Vinton G. Cerf	431

Chapter 5	The Link Layer: Links, Access Networks, and LANs	433
5.1	Introduction to the Link Layer	434
5.1.1	The Services Provided by the Link Layer	436
5.1.2	Where Is the Link Layer Implemented?	437
5.2	Error-Detection and -Correction Techniques	438
5.2.1	Parity Checks	440
5.2.2	Checksumming Methods	442
5.2.3	Cyclic Redundancy Check (CRC)	443
5.3	Multiple Access Links and Protocols	445
5.3.1	Channel Partitioning Protocols	448
5.3.2	Random Access Protocols	449
5.3.3	Taking-Turns Protocols	459
5.3.4	DOCSIS: The Link-Layer Protocol for Cable Internet Access	460

5.4	Switched Local Area Networks	461
5.4.1	Link-Layer Addressing and ARP	462
5.4.2	Ethernet	469
5.4.3	Link-Layer Switches	476
5.4.4	Virtual Local Area Networks (VLANs)	482
5.5	Link Virtualization: A Network as a Link Layer	486
5.5.1	Multiprotocol Label Switching (MPLS)	487
5.6	Data Center Networking	490
5.7	Retrospective: A Day in the Life of a Web Page Request	495
5.7.1	Getting Started: DHCP, UDP, IP, and Ethernet	495
5.7.2	Still Getting Started: DNS and ARP	497
5.7.3	Still Getting Started: Intra-Domain Routing to the DNS Server	498
5.7.4	Web Client-Server Interaction: TCP and HTTP	499
5.8	Summary	500
	Homework Problems and Questions	502
	Wireshark Labs: Ethernet and ARP, DHCP	510
	Interview: Simon S. Lam	511

Chapter 6 Wireless and Mobile Networks 513

6.1	Introduction	514
6.2	Wireless Links and Network Characteristics	519
6.2.1	CDMA	522
6.3	WiFi: 802.11 Wireless LANs	526
6.3.1	The 802.11 Architecture	527
6.3.2	The 802.11 MAC Protocol	531
6.3.3	The IEEE 802.11 Frame	537
6.3.4	Mobility in the Same IP Subnet	541
6.3.5	Advanced Features in 802.11	542
6.3.6	Personal Area Networks: Bluetooth and Zigbee	544
6.4	Cellular Internet Access	546
6.4.1	An Overview of Cellular Network Architecture	547
6.4.2	3G Cellular Data Networks: Extending the Internet to Cellular Subscribers	550
6.4.3	On to 4G: LTE	553
6.5	Mobility Management: Principles	555
6.5.1	Addressing	557
6.5.2	Routing to a Mobile Node	559
6.6	Mobile IP	564
6.7	Managing Mobility in Cellular Networks	570
6.7.1	Routing Calls to a Mobile User	571
6.7.2	Handoffs in GSM	572

6.8	Wireless and Mobility: Impact on Higher-Layer Protocols	575
6.9	Summary	578
	Homework Problems and Questions	578
	Wireshark Lab: IEEE 802.11 (WiFi)	583
	Interview: Deborah Estrin	584

Chapter 7 Multimedia Networking **587**

7.1	Multimedia Networking Applications	588
7.1.1	Properties of Video	588
7.1.2	Properties of Audio	590
7.1.3	Types of Multimedia Network Applications	591
7.2	Streaming Stored Video	593
7.2.1	UDP Streaming	595
7.2.2	HTTP Streaming	596
7.2.3	Adaptive Streaming and DASH	600
7.2.4	Content Distribution Networks	602
7.2.5	Case Studies: Netflix, YouTube, and Kankan	608
7.3	Voice-over-IP	612
7.3.1	Limitations of the Best-Effort IP Service	612
7.3.2	Removing Jitter at the Receiver for Audio	614
7.3.3	Recovering from Packet Loss	617
7.3.4	Case Study: VoIP with Skype	620
7.4	Protocols for Real-Time Conversational Applications	623
7.4.1	RTP	624
7.4.2	SIP	627
7.5	Network Support for Multimedia	632
7.5.1	Dimensioning Best-Effort Networks	634
7.5.2	Providing Multiple Classes of Service	636
7.5.3	Diffserv	648
7.5.4	Per-Connection Quality-of-Service (QoS) Guarantees: Resource Reservation and Call Admission	652
7.6	Summary	655
	Homework Problems and Questions	656
	Programming Assignment	666
	Interview: Henning Schulzrinne	668

Chapter 8 Security in Computer Networks **671**

8.1	What Is Network Security?	672
8.2	Principles of Cryptography	675
8.2.1	Symmetric Key Cryptography	676
8.2.2	Public Key Encryption	683

8.3	Message Integrity and Digital Signatures	688
8.3.1	Cryptographic Hash Functions	689
8.3.2	Message Authentication Code	691
8.3.3	Digital Signatures	693
8.4	End-Point Authentication	700
8.4.1	Authentication Protocol <i>ap1.0</i>	700
8.4.2	Authentication Protocol <i>ap2.0</i>	701
8.4.3	Authentication Protocol <i>ap3.0</i>	702
8.4.4	Authentication Protocol <i>ap3.1</i>	703
8.4.5	Authentication Protocol <i>ap4.0</i>	703
8.5	Securing E-Mail	705
8.5.1	Secure E-Mail	706
8.5.2	PGP	710
8.6	Securing TCP Connections: SSL	711
8.6.1	The Big Picture	713
8.6.2	A More Complete Picture	716
8.7	Network-Layer Security: IPsec and Virtual Private Networks	718
8.7.1	IPsec and Virtual Private Networks (VPNs)	718
8.7.2	The AH and ESP Protocols	720
8.7.3	Security Associations	720
8.7.4	The IPsec Datagram	721
8.7.5	IKE: Key Management in IPsec	725
8.8	Securing Wireless LANs	726
8.8.1	Wired Equivalent Privacy (WEP)	726
8.8.2	IEEE 802.11i	728
8.9	Operational Security: Firewalls and Intrusion Detection Systems	731
8.9.1	Firewalls	731
8.9.2	Intrusion Detection Systems	739
8.10	Summary	742
	Homework Problems and Questions	744
	Wireshark Lab: SSL	752
	IPsec Lab	752
	Interview: Steven M. Bellovin	753

Chapter 9 Network Management 755

9.1	What Is Network Management?	756
9.2	The Infrastructure for Network Management	760
9.3	The Internet-Standard Management Framework	764
9.3.1	Structure of Management Information: SMI	766
9.3.2	Management Information Base: MIB	770

9.3.3	SNMP Protocol Operations and Transport Mappings	772
9.3.4	Security and Administration	775
9.4	ASN.1	778
9.5	Conclusion	783
	Homework Problems and Questions	783
	Interview: Jennifer Rexford	786
	References	789
	Index	823

COMPUTER NETWORKING

SIXTH EDITION

A Top-Down Approach



This page intentionally left blank



Computer Networks and the Internet

Today's Internet is arguably the largest engineered system ever created by mankind, with hundreds of millions of connected computers, communication links, and switches; with billions of users who connect via laptops, tablets, and smartphones; and with an array of new Internet-connected devices such as sensors, Web cams, game consoles, picture frames, and even washing machines. Given that the Internet is so large and has so many diverse components and uses, is there any hope of understanding how it works? Are there guiding principles and structure that can provide a foundation for understanding such an amazingly large and complex system? And if so, is it possible that it actually could be both interesting *and* fun to learn about computer networks? Fortunately, the answers to all of these questions is a resounding YES! Indeed, it's our aim in this book to provide you with a modern introduction to the dynamic field of computer networking, giving you the principles and practical insights you'll need to understand not only today's networks, but tomorrow's as well.

This first chapter presents a broad overview of computer networking and the Internet. Our goal here is to paint a broad picture and set the context for the rest of this book, to see the forest through the trees. We'll cover a lot of ground in this introductory chapter and discuss a lot of the pieces of a computer network, without losing sight of the big picture.