4th Edition

Computer Networking

A Top-Down Approach

James F. Kurose
University of Massachusetts, Amherst

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Keith W. Ross
Polytechnic University, Brooklyn

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About the Authors

Jim Kurose

Jim Kurose is a Distinguished University Professor of Computer Science at the University of Massachusetts, Amherst.

Dr. Kurose has received a number of recognitions for his educational activities including Outstanding Teacher Awards from the National Technological University (eight times), the University of Massachusetts, and the Northeast Association of Graduate Schools. He received the IEEE Taylor Booth Education Medal and was recognized for his leadership of Massachusetts' Commonwealth Information Technology Initiative. He has been the recipient of a GE Fellowship, an IBM Faculty Development Award, and a Lilly Teaching Fellowship.

Dr. Kurose is a former Editor-in-Chief of *IEEE Transactions on Communications* and of *IEEE/ACM Transactions on Networking*. He has been active in the program committees for *IEEE Infocom, ACM SIGCOMM, ACM Internet Measurement Conference,* and *ACM SIGMETRICS* for a number of years and has served as Technical Program Co-Chair for those conferences. He is a Fellow of the IEEE and the ACM. His research interests include network protocols and architecture, network measurement, sensor networks, multimedia communication, and modeling and performance evaluation. He holds a PhD in Computer Science from Columbia University.

Keith Ross

Keith Ross is the Leornard J. Shustek Distinguished Chair Professor in Computer Science at Polytechnic University in Brooklyn. From 1985 to 1998 he was a professor in the Department of Systems Engineering at the University of Pennsylvania. From 1998 to 2003 he was a professor in the Multimedia Communications Department at Institute Eurecom in France. Keith Ross is also the principal founder and original CEO of Wimba, which develops Voice over IP and streaming technologies for e-learning markets.

Professor Ross's research interests are in peer-to-peer networking, Internet measurement, video streaming, Web caching, content distribution networks, network security, Voice over IP, and stochastic modeling. He is an IEEE Fellow, and is currently associate editor for *IEEE/ACM Transactions on Networking*. He has served as an advisor to the Federal Trade Commission on P2P file sharing. He has been active in the program committees for *IEEE Infocom, ACM SIGCOMM, ACM Multimedia, ACM Internet Measurement Conference,* and *ACM SIGMETRICS*. He holds a PhD in Computer, Information, and Control Engineering from the University of Michigan.

Publisher	Greg Tobin
Executive Editor	Michael Hirsch
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To Julie and our three precious
ones—Chris, Charlie, and Nina
JFK

To my wonderful wife, Véronique,
(she's such a great cook among other things!),
and our three daughters, Cécile, Claire, and Katie
KWR

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Front Matter

iii. In Keith's bio, *"Leornard" should be "Leonard"*

Chapter 1

Page 30, line 11: boldface "forwarding table"

Page 58: Include a paragraph indentation for paragraph beginning with "In closing...."

Page 63, line 35 "Andreesen" should be "Andreessen"

Page 68, R15: replace "user requires" with "user transmits continuously at"

Page 69, Replace "R26" with "R28"

Chapter 2

Page 142. line 21: http://www.intenic.net should be http://www.internic.net

Page 158, line 9: remove "(see Figure 2.29)"

Page 161, Figure 2.30: Replace with Figure 2.26 from 3rd edition. THIS IS A MUST CHANGE

Chapter 3

Page 250, equation for DevRTT: the bar on the second line should be moved to the end of the first line (see 3rd edition)

Page 303, P41: If possible, remove part (b) of P41; and relabel part (c) as (b).

Page 303, P42, part b: remove "8 S/R>" and align the equation to the left

Chapter 4

Page 367, 7 lines from bottom: replace "securely nonsecure" with "securely in the non-secure"

Page 426, figure: replace "X" in figure with lowercase "x" (and not bold)

Page 427, problem P33: replace "P21" with "P22".

Chapter 5

Page 485 in Principles in Practice: Add the title: SNIFFING A SWITCHED LAN: SWITCH POISONING

Page 485 in Principles in Practice, 14 lines down: replace "souce" with "source"

Chapter 6

Figure 6.9: In the text on the right side of the Figure, "a. Active scanning" should be "b. Active Scanning"

Chapter 8

Page 699, five lines from bottom: replace (m, H(m')) with (m', H(m'))

Preface

Welcome to the fourth edition of *Computer Networking: A Top-Down Approach.* Since the publication of the first edition seven years ago, our book has been adopted for use at many hundreds of colleges and universities, translated into more than 10 languages, and used by over one-hundred thousand students and practitioners worldwide. We've heard from many of these readers and have been overwhelmed by the positive response.

What's New in the Fourth Edition?

We think one important reason for this success has been that our book continues to offer a fresh and timely approach to computer networking instruction. We've made changes in this fourth edition, but we've also kept unchanged what we believe (and the instructors and students who have used our book have confirmed) to be the most important aspects of this book: its top-down approach, its focus on the Internet and a modern treatment of computer networking, its attention to both principles and practice, and its accessible style and approach toward learning about computer networking.

Nevertheless, we've made many important changes in the fourth edition. Given the tremendous importance of network security, we've increased our focus on network security, introducing network security issues in a new section in the very first chapter, adding new security-related material in all chapters, and updating and expanding our coverage of network security in Chapter 8 (which has been dedicated to the topic of network security since our very first edition). We've also updated and expanded our coverage of wireless networks, with additional new material on 802.11 (WiFi), 802.16 (WiMAX), and cellular networks. Our coverage of P2P applications—an increasingly important family of application protocols—includes not only file-sharing protocols, but also file-distribution protocols such as BitTorrent and new peer-to-peer (P2P) multimedia applications such as Voice over IP using Skype. Our chapters on local area networks and multimedia networking have also been streamlined and updated to reflect changes in both the principles and practice in these areas. We've also streamlined Chapter 1 while adding new material on end-to-end throughput analysis. Throughout the book, we've included new state-of-the-art examples and up-to-date references. In the end-of-chapter material, we've added new homework problems, as well as additional hands-on Ethereal labs.

Audience

This textbook is for a first course on computer networking. It can be used in both computer science and electrical engineering departments. In terms of programming languages, the book assumes only that the student has experience with C, C++, or Java (and even then only in a few places). Although this book is more precise and analytical than many other introductory computer networking texts, it rarely uses any mathematical concepts that are not taught in high school. We have made a deliberate effort to avoid using any advanced calculus, probability, or stochastic process concepts (although we've included some homework problems for students with this advanced background). The book is therefore appropriate for undergraduate courses and for first-year graduate courses. It should also be useful to practitioners in the telecommunications industry.

What Is Unique about This Textbook?

The subject of computer networking is enormously complex, involving many concepts, protocols, and technologies that are woven together in an intricate manner. To cope with this scope and complexity, many computer networking texts are often organized around the "layers" of a network architecture. With a layered organization, students can see through the complexity of computer networking—they learn about the distinct concepts and protocols in one part of the architecture while seeing the big picture of how all parts fit together. From a pedagogical perspective, our personal experience has been that such a layered approach is indeed highly desirable. Nevertheless, we have found the traditional approach of teaching—bottom up, that is, from the physical layer towards the application layer—is not the best approach for a modern course on computer networking.

A Top-Down Approach

Our book broke new ground 7 years ago by treating networking in a top-down manner—that is, by beginning at the application layer and working its way down toward the physical layer. The top-down approach has several important benefits. First, it places emphasis on the application layer (a "high growth area" in networking). Indeed, many of the recent revolutions in computer networking—including the Web, peer-to-peer file sharing, and media streaming—have taken place at the application layer. An early emphasis on application-layer issues differs from the approaches taken in most other texts, which have only a small amount of material on network applications, their requirements, application-layer paradigms (e.g., client-server and peer-to-peer), and application programming interfaces.

Second, our experience as instructors (and that of many instructors who have used this text) has been that teaching networking applications near the beginning of the course is a powerful motivational tool. Students are thrilled to learn about how networking applications work—applications such as e-mail and the Web, which most students use on a daily basis. Once a student understands the applications, the student can then understand the network services needed to support these applications. The student can then, in turn, examine the various ways in which such services might be provided and implemented in the lower layers. Covering applications early thus provides motivation for the remainder of the text.

Third, a top-down approach enables instructors to introduce network application development at an early stage. Students not only see how popular applications and protocols work, but also learn how easy it is to create their own network applications and application-level protocols. With the top-down approach, students get early exposure to the notions of application programming interfaces (APIs), service models, and protocols—important concepts that resurface in all subsequent layers. By providing socket programming examples in Java, we highlight the central ideas without confusing students with complex code. Undergraduates in electrical engineering and computer science should not have difficulty following the Java code.

An Internet Focus

With this fourth edition, we have dropped the phrase "Featuring the Internet" from the title, but does this mean that we have dropped our focus on the Internet? Indeed not (and nothing could be farther from the case)! Instead, since the Internet has become so pervasive, we felt that any networking textbook must have a significant focus on the Internet, and thus this phrase was somewhat unnecessary. As in our first three editions, we continue to use the Internet's architecture and protocols as primary vehicles for studying fundamental computer networking concepts. Of course, we also include concepts and protocols from other network architectures. But the spotlight is clearly on the Internet, a fact reflected in our organizing the book around the Internet's five-layer architecture: the application, transport, network, link, and physical layers.

Another benefit of spotlighting the Internet is that most computer science and electrical engineering students are eager to learn about the Internet and its protocols. They know that the Internet is a revolutionary and disruptive technology and can see that it is profoundly changing our world. Given the enormous relevance of the Internet, students are naturally curious about what is "under the hood." Thus, it is easy for an instructor to get students excited about basic principles when using the Internet as the guiding focus.

Addressing Principles

Two of the unique features of the book—its top-down approach and its focus on the Internet—have appeared in the title of the first three editions of our book. If we could have squeezed a *third* phrase into the subtitle, it would have contained the word *principles*. The field of networking is now mature enough that a number of fundamentally important issues can be identified. For example, in the transport layer, the fundamental issues include reliable communication over an unreliable network layer, connection establishment/teardown and handshaking, congestion and flow control, and multiplexing. Two fundamentally important network-layer issues are determining "good" paths between two routers and interconnecting a large number of heterogeneous networks. In the data link layer, a fundamental problem is sharing a multiple access channel. In network security, techniques for providing confidentiality, authentication, and message integrity are all based on cryptographic fundamentals. This text identifies fundamental networking issues and studies approaches towards addressing these issues. The student learning these principles will gain knowledge with a long "shelf life"—long after today's network standards and protocols have become obsolete, the principles they embody will remain important and relevant. We believe that the combination of using the Internet to get the student's foot in the door and then emphasizing fundamental issues and solution approaches will allow the student to quickly understand just about any networking technology.

The Web Site

Purchasing this textbook grants each reader six months of access to a companion Web site for all book readers at http://www.aw.com/kurose-ross, which includes:

- *Interactive learning material.* The Web site contains several interactive Java applets, animating many of the key networking concepts. The site also makes available interactive quizzes that permit students to check their basic understanding of the subject matter. Professors can integrate these interactive features into their lectures or use them as mini labs.
- *Additional technical material.* As we have added new material in each edition of our book, we've had to remove coverage of some existing topics to keep the book at manageable length. For example, to make room for new material on switched LANs, we've removed material on hubs and bridges; to make room for new security material, we've removed material on older security topics (e.g., Kerberos, and key distribution schemes). Material that appeared in earlier editions of the text is still of interest, and can be found on the book's Web site.
- *Programming assignments.* The Web site also provides a number of detailed programming assignments. The programming assignments include building a multithreaded Web server, building an e-mail client with a GUI interface, programming the sender and receiver sides of a reliable data transport protocol, programming a distributed routing algorithm, and more.
- *Ethereal labs.* One's understanding of network protocols can be greatly deepened by seeing them in action. The Web site provides numerous Ethereal assignments that enable students to actually observe the sequence of messages exchanged

between two protocol entities. The Web site includes separate Ethereal labs on HTTP, DNS, TCP, UDP, IP, ICMP, Ethernet, ARP, WiFi, and SSL.

Pedagogical Features

We have each been teaching computer networking for more than 20 years. Together, we bring more than 45 years of teaching experience to this text, during which time we have taught many thousands of students. We have also been active researchers in computer networking during this time. (In fact, Jim and Keith first met each other as master's students in a computer networking course taught by Mischa Schwartz in 1979 at Columbia University.) We think all this gives us a good perspective on where networking has been and where it is likely to go in the future. Nevertheless, we have resisted temptations to bias the material in this book towards our own pet research projects. We figure you can visit our personal Web sites if you are interested in our research. Thus, this book is about modern computer networking—it is about contemporary protocols and technologies as well as the underlying principles behind these protocols and technologies. We also believe that learning (and teaching!) about networking can be fun. A sense of humor, use of analogies, and real-world examples in this book will hopefully make this material more fun.

Historical Sidebars, Principles in Practice, and a Focus on Security

The field of computer networking has a rich and fascinating history. We have made a special effort in the text to tell the history of computer networking. This is done with a special historical section in Chapter 1 and with about a dozen historical sidebars sprinkled throughout the chapters. In these historical pieces, we cover the invention of packet switching, the evolution of the Internet, the birth of major networking giants such as Cisco and 3Com, and many other important events. Students will be stimulated by these historical pieces. We include special sidebars that highlight important principles in computer networking. These sidebars will help students appreciate some of the fundamental concepts being applied in modern networking. Some of our increased coverage of network security appears in a new series of "Focus on Security" sidebars in each of the core chapters of this book.

Interviews

We have included yet another original feature that should inspire and motivate students—interviews with renowned innovators in the field of networking. We provide interviews with Len Kleinrock, Bram Cohen, Sally Floyd, Vint Cerf, Simon Lam, Charlie Perkins, Henning Schulzrinne, Steven Bellovin, and Jeff Case.

Supplements for Instructors

We provide a complete supplements package to aid instructors in teaching this course. This material can be accessed from Addison-Wesley's Instructor's Resource Center (http://www.aw.com/irc). Visit the Instructor's Resource Center or send e-mail to computing@aw.com for information about accessing these instructor's supplements.

- *PowerPoint® slides.* We provide PowerPoint slides for all nine chapters. The slides cover each chapter in detail. They use graphics and animations (rather than relying only on monotonous text bullets) to make the slides interesting and visually appealing. We provide the original PowerPoint slides so you can customize them to best suit your own teaching needs. Some of these slides have been contributed by other instructors who have taught from our book.
- *Homework solutions.* We provide a solutions manual for the homework problems in the text, programming assignments, and Ethereal labs.

Chapter Dependencies

The first chapter of this text presents a self-contained overview of computer networking. Introducing many key concepts and terminology, this chapter sets the stage for the rest of the book. All of the other chapters directly depend on this first chapter. We recommend that, after completing Chapter 1, instructors cover Chapters 2 through 5 in sequence, following our top-down philosophy. Each of these five chapters leverages material from the preceding chapters.

After completing the first five chapters, the instructor has quite a bit of flexibility. There are no interdependencies among the last four chapters, so they can be taught in any order. However, each of the last four chapters depends on the material in the first five chapters. Many instructors teach the first five chapters and then teach one of the last four chapters for "dessert."

One Final Note: We'd Love to Hear from You

We encourage instructors and students to create new Java applets that illustrate the concepts and protocols in this book. If you have an applet that you think would be appropriate for this text, please submit it to the authors. If the applet (including notation and terminology) is appropriate, we will be happy to include it on the text's Web site, with an appropriate reference to the authors of the applet. As noted above, we also encourage instructors to send us new homework problems (and solutions) that would complement the current homework problems. We will post these on the instructor-only portion of the Web site.

We also encourage students and instructors to e-mail us about any comments they might have about our book. It's been wonderful for us to hear from so many instructors and students from around the world about our first three editions. As the saying goes, "Keep those cards and letters coming!" Seriously, please *do* continue to send us interesting URLs, point out typos, disagree with any of our claims, and tell us what works and what doesn't work. Tell us what you think should or shouldn't be included in the next edition. Send your e-mail to kurose@cs.umass.edu and ross@poly.edu.

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Since we began writing this book in 1996, many people have given us invaluable help and have been influential in shaping our thoughts on how to best organize and teach a networking course. We want to say A BIG THANKS to everyone who has helped us from the earliest first drafts of this book, up to this fourth edition. We are also *very* thankful to the hundreds of readers from around the world—students, faculty, practitioners—who have sent us thoughts and comments on earlier editions of the book and suggestions for future editions of the book. Special thanks go out to:

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