

# Computer Networking

A Top-Down Approach



sixth edition

**KUROSE** | **ROSS**

# COMPUTER

SIXTH EDITION

# NETWORKING

A Top-Down Approach



**JAMES F. KUROSE**

*University of Massachusetts, Amherst*

**KEITH W. ROSS**

*Polytechnic Institute of NYU*

**PEARSON**

Boston Columbus Indianapolis New York San Francisco Upper Saddle River  
Amsterdam Cape Town Dubai London Madrid Milan Munich Paris Montréal Toronto  
Delhi Mexico City São Paulo Sydney Hong Kong Seoul Singapore Taipei Tokyo

**Vice President and Editorial Director, ECS:**

Marcia Horton

**Editor in Chief:** Michael Hirsch

**Editorial Assistant:** Emma Snider

**Vice President Marketing:** Patrice Jones

**Marketing Manager:** Yez Alayan

**Marketing Coordinator:** Kathryn Ferranti

**Vice President and Director of Production:**

Vince O'Brien

**Managing Editor:** Jeff Holcomb

**Senior Production Project Manager:**

Marilyn Lloyd

**Manufacturing Manager:** Nick Sklitsis

**Operations Specialist:** Lisa McDowell

**Art Director, Cover:** Anthony Gemmellaro

**Art Coordinator:** Janet Theurer/

Theurer Briggs Design

**Art Studio:** Patrice Rossi Calkin/

Rossi Illustration and Design

**Cover Designer:** Liz Harasymcuk

**Text Designer:** Joyce Cosentino Wells

**Cover Image:** ©Fancy/Alamy

**Media Editor:** Dan Sandin

**Full-Service Vendor:** PreMediaGlobal

**Senior Project Manager:** Andrea Stefanowicz

**Printer/Binder:** Edwards Brothers

**Cover Printer:** Lehigh-Phoenix Color

This book was composed in Quark. Basal font is Times. Display font is Berkeley.

---

Copyright © 2013, 2010, 2008, 2005, 2003 by Pearson Education, Inc., publishing as Addison-Wesley. All rights reserved. Manufactured in the United States of America. This publication is protected by Copyright, and permission should be obtained from the publisher prior to any prohibited reproduction, storage in a retrieval system, or transmission in any form or by any means, electronic, mechanical, photocopying, recording, or likewise. To obtain permission(s) to use material from this work, please submit a written request to Pearson Education, Inc., Permissions Department, One Lake Street, Upper Saddle River, New Jersey 07458, or you may fax your request to 201-236-3290.

Many of the designations by manufacturers and sellers to distinguish their products are claimed as trademarks. Where those designations appear in this book, and the publisher was aware of a trademark claim, the designations have been printed in initial caps or all caps.

**Library of Congress Cataloging-in-Publication Data**

Kurose, James F.

Computer networking : a top-down approach / James F. Kurose, Keith W. Ross.—6th ed.

p. cm.

Includes bibliographical references and index.

ISBN-13: 978-0-13-285620-1

ISBN-10: 0-13-285620-4

1. Internet. 2. Computer networks. I. Ross, Keith W., 1956- II. Title.

TK5105.875.I57K88 2012

004.6—dc23

2011048215

10 9 8 7 6 5 4 3 2 1

**PEARSON**

ISBN-10: 0-13-285620-4

ISBN-13: 978-0-13-285620-1

# 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 Leonard J. Shustek Chair Professor and Head of the Computer Science Department at Polytechnic Institute of NYU. Before joining NYU-Poly in 2003, he was a professor at the University of Pennsylvania (13 years) and a professor at Eurecom Institute (5 years). He received a B.S.E.E from Tufts University, a M.S.E.E. from Columbia University, and a Ph.D. in Computer and Control Engineering from The University of Michigan. Keith Ross is also the founder and original CEO of Wimba, which develops online multimedia applications for e-learning and was acquired by Blackboard in 2010.

Professor Ross's research interests are in security and privacy, social networks, peer-to-peer networking, Internet measurement, video streaming, content distribution networks, and stochastic modeling. He is an IEEE Fellow, recipient of the Infocom 2009 Best Paper Award, and recipient of 2011 and 2008 Best Paper Awards for Multimedia Communications (awarded by IEEE Communications Society). He has served on numerous journal editorial boards and conference program committees, including *IEEE/ACM Transactions on Networking*, *ACM SIGCOMM*, *ACM CoNext*, and *ACM Internet Measurement Conference*. He also has served as an advisor to the Federal Trade Commission on P2P file sharing.



*This page intentionally left blank*

To Julie and our three precious  
ones—Chris, Charlie, and Nina  
JFK

A big THANKS to my professors, colleagues,  
and students all over the world.  
KWR

*This page intentionally left blank*

# Preface

Welcome to the sixth edition of *Computer Networking: A Top-Down Approach*. Since the publication of the first edition 12 years ago, our book has been adopted for use at many hundreds of colleges and universities, translated into 14 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 Sixth 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 sixth 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, the sixth edition has been revised and updated substantially:

- The Companion Web site has been significantly expanded and enriched to include VideoNotes and interactive exercises, as discussed later in this Preface.
- In Chapter 1, the treatment of access networks has been modernized, and the description of the Internet ISP ecosystem has been substantially revised, accounting for the recent emergence of content provider networks, such as Google's. The presentation of packet switching and circuit switching has also been reorganized, providing a more topical rather than historical orientation.
- In Chapter 2, Python has replaced Java for the presentation of socket programming. While still explicitly exposing the key ideas behind the socket API, Python code is easier to understand for the novice programmer. Moreover, unlike Java, Python provides access to raw sockets, enabling students to build a larger variety of network applications. Java-based socket programming labs have been replaced with corresponding Python labs, and a new Python-based ICMP Ping lab has been added. As always, when material is retired from the book, such as Java-based socket programming material, it remains available on the book's Companion Web site (see following text).
- In Chapter 3, the presentation of one of the reliable data transfer protocols has been simplified and a new sidebar on TCP splitting, commonly used to optimize the performance of cloud services, has been added.
- In Chapter 4, the section on router architectures has been significantly updated, reflecting recent developments and practices in the field. Several new integrative sidebars involving DNS, BGP, and OSPF are included.



- Chapter 5 has been reorganized and streamlined, accounting for the ubiquity of switched Ethernet in local area networks and the consequent increased use of Ethernet in point-to-point scenarios. Also, a new section on data center networking has been added.
- Chapter 6 has been updated to reflect recent advances in wireless networks, particularly cellular data networks and 4G services and architecture.
- Chapter 7, which focuses on multimedia networking, has gone through a major revision. The chapter now includes an in-depth discussion of streaming video, including adaptive streaming, and an entirely new and modernized discussion of CDNs. A newly added section describes the Netflix, YouTube, and Kankan video streaming systems. The material that has been removed to make way for these new topics is still available on the Companion Web site.
- Chapter 8 now contains an expanded discussion on endpoint authentication.
- Significant new material involving end-of-chapter problems has been added. As with all previous editions, homework problems have been revised, added, and removed.

## 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++, Java, or Python (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

indeed works well. Nevertheless, we have found that 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 12 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 feedback we received from teachers and students alike have confirmed that this top-down approach has many advantages and does indeed work well pedagogically. 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 socket programming, service models, and protocols—important concepts that resurface in all subsequent layers. By providing socket programming examples in Python, we highlight the central ideas without confusing students with complex code. Undergraduates in electrical engineering and computer science should not have difficulty following the Python code.

## An Internet Focus

Although we dropped the phrase “Featuring the Internet” from the title of this book with the fourth edition, this doesn’t mean that we dropped our focus on the Internet! Indeed, nothing could be further from the case! Instead, since the Internet has become so pervasive, we felt that any networking textbook must have a significant