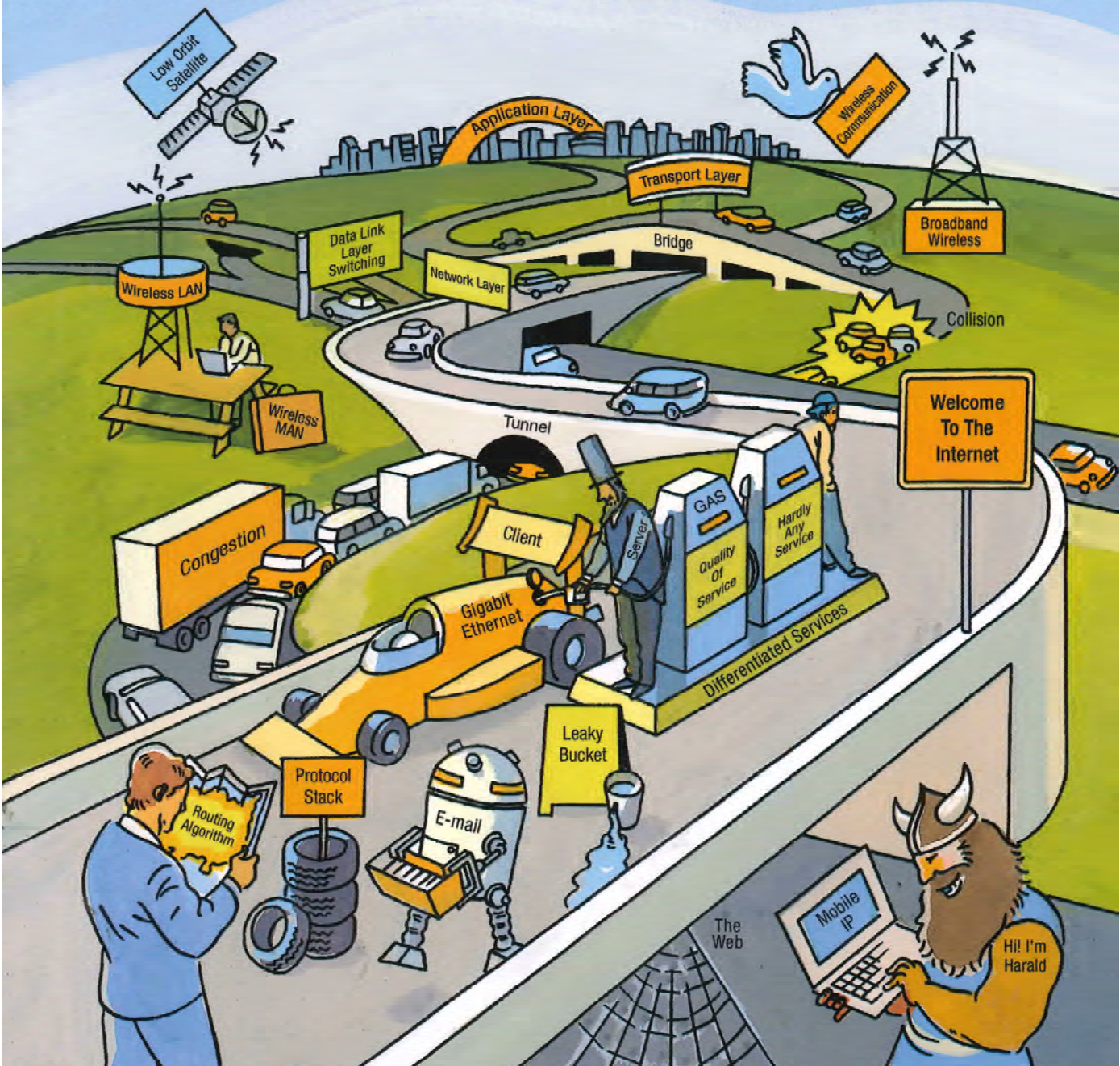


FOURTH EDITION

Computer Networks

ANDREW S. TANENBAUM



Computer Networks

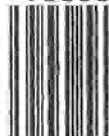
Fourth Edition

ISBN 0-13-066102-3



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Amsterdam, The Netherlands*



Prentice Hall PTR
Upper Saddle River, NJ 07458
www.phptr.com

Library of Congress Cataloging-in-Publication Data

Tanenbaum, Andrew S.
Computer networks / Andrew S. Tanenbaum.--4th ed.
p. cm.
Includes bibliographical references.
ISBN 0-13-066102-3
1. Computer networks. I. Title.
TK5105.5 .T36 2002
004.6--dc21 2002029263

Editorial/production supervision: *Patti Guerrieri*
Cover design director: *Jerry Votta*
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Interior graphics: *Hadel Studio*
Typesetting: *Andrew S. Tanenbaum*
Manufacturing buyer: *Maura Zaldivar*
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Marketing manager: *Dan DePasquale*



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Publishing as Prentice Hall PTR
Upper Saddle River, New Jersey 07458

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Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-066102-3

Pearson Education LTD.
Pearson Education Australia PTY, Limited
Pearson Education Singapore, Pte. Ltd.
Pearson Education North Asia Ltd.
Pearson Education Canada, Ltd.
Pearson Educación de México, S.A. de C.V.
Pearson Education — Japan
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Although this book primarily focuses on networks, many of the topics are also important in distributed systems. For more information about distributed systems, see (Tanenbaum and Van Steen, 2002).

1.1 USES OF COMPUTER NETWORKS

Before we start to examine the technical issues in detail, it is worth devoting some time to pointing out why people are interested in computer networks and what they can be used for. After all, if nobody were interested in computer networks, few of them would be built. We will start with traditional uses at companies and for individuals and then move on to recent developments regarding mobile users and home networking.

1.1.1 Business Applications

Many companies have a substantial number of computers. For example, a company may have separate computers to monitor production, keep track of inventories, and do the payroll. Initially, each of these computers may have worked in isolation from the others, but at some point, management may have decided to connect them to be able to extract and correlate information about the entire company.

Put in slightly more general form, the issue here is **resource sharing**, and the goal is to make all programs, equipment, and especially data available to anyone on the network without regard to the physical location of the resource and the user. An obvious and widespread example is having a group of office workers share a common printer. None of the individuals really needs a private printer, and a high-volume networked printer is often cheaper, faster, and easier to maintain than a large collection of individual printers.

However, probably even more important than sharing physical resources such as printers, scanners, and CD burners, is sharing information. Every large and medium-sized company and many small companies are vitally dependent on computerized information. Most companies have customer records, inventories, accounts receivable, financial statements, tax information, and much more online. If all of its computers went down, a bank could not last more than five minutes. A modern manufacturing plant, with a computer-controlled assembly line, would not last even that long. Even a small travel agency or three-person law firm is now highly dependent on computer networks for allowing employees to access relevant information and documents instantly.

For smaller companies, all the computers are likely to be in a single office or perhaps a single building, but for larger ones, the computers and employees may be scattered over dozens of offices and plants in many countries. Nevertheless, a sales person in New York might sometimes need access to a product inventory

database in Singapore. In other words, the mere fact that a user happens to be 15,000 km away from his data should not prevent him from using the data as though they were local. This goal may be summarized by saying that it is an attempt to end the “tyranny of geography.”

In the simplest of terms, one can imagine a company’s information system as consisting of one or more databases and some number of employees who need to access them remotely. In this model, the data are stored on powerful computers called **servers**. Often these are centrally housed and maintained by a system administrator. In contrast, the employees have simpler machines, called **clients**, on their desks, with which they access remote data, for example, to include in spreadsheets they are constructing. (Sometimes we will refer to the human user of the client machine as the “client,” but it should be clear from the context whether we mean the computer or its user.) The client and server machines are connected by a network, as illustrated in Fig. 1-1. Note that we have shown the network as a simple oval, without any detail. We will use this form when we mean a network in the abstract sense. When more detail is required, it will be provided.

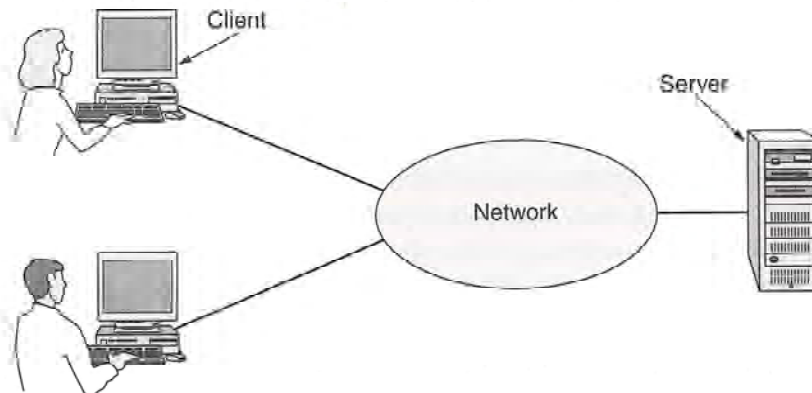


Figure 1-1. A network with two clients and one server.

This whole arrangement is called the **client-server model**. It is widely used and forms the basis of much network usage. It is applicable when the client and server are both in the same building (e.g., belong to the same company), but also when they are far apart. For example, when a person at home accesses a page on the World Wide Web, the same model is employed, with the remote Web server being the server and the user’s personal computer being the client. Under most conditions, one server can handle a large number of clients.

If we look at the client-server model in detail, we see that two processes are involved, one on the client machine and one on the server machine. Communication takes the form of the client process sending a message over the network to the server process. The client process then waits for a reply message. When the serv-

er process gets the request, it performs the requested work or looks up the requested data and sends back a reply. These messages are shown in Fig. 1-2.

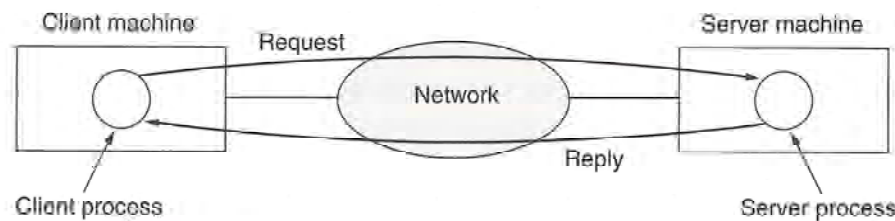


Figure 1-2. The client-server model involves requests and replies.

A second goal of setting up a computer network has to do with people rather than information or even computers. A computer network can provide a powerful **communication medium** among employees. Virtually every company that has two or more computers now has **e-mail (electronic mail)**, which employees generally use for a great deal of daily communication. In fact, a common gripe around the water cooler is how much e-mail everyone has to deal with, much of it meaningless because bosses have discovered that they can send the same (often content-free) message to all their subordinates at the push of a button.

But e-mail is not the only form of improved communication made possible by computer networks. With a network, it is easy for two or more people who work far apart to write a report together. When one worker makes a change to an on-line document, the others can see the change immediately, instead of waiting several days for a letter. Such a speedup makes cooperation among far-flung groups of people easy where it previously had been impossible.

Yet another form of computer-assisted communication is videoconferencing. Using this technology, employees at distant locations can hold a meeting, seeing and hearing each other and even writing on a shared virtual blackboard. Videoconferencing is a powerful tool for eliminating the cost and time previously devoted to travel. It is sometimes said that communication and transportation are having a race, and whichever wins will make the other obsolete.

A third goal for increasingly many companies is doing business electronically with other companies, especially suppliers and customers. For example, manufacturers of automobiles, aircraft, and computers, among others, buy subsystems from a variety of suppliers and then assemble the parts. Using computer networks, manufacturers can place orders electronically as needed. Being able to place orders in real time (i.e., as needed) reduces the need for large inventories and enhances efficiency.

A fourth goal that is starting to become more important is doing business with consumers over the Internet. Airlines, bookstores, and music vendors have discovered that many customers like the convenience of shopping from home. Consequently, many companies provide catalogs of their goods and services on-line and take orders on-line. This sector is expected to grow quickly in the future. It is called **e-commerce (electronic commerce)**.

1.1.2 Home Applications

In 1977, Ken Olsen was president of the Digital Equipment Corporation, then the number two computer vendor in the world (after IBM). When asked why Digital was not going after the personal computer market in a big way, he said: "There is no reason for any individual to have a computer in his home." History showed otherwise and Digital no longer exists. Why do people buy computers for home use? Initially, for word processing and games, but in recent years that picture has changed radically. Probably the biggest reason now is for Internet access. Some of the more popular uses of the Internet for home users are as follows:

1. Access to remote information.
2. Person-to-person communication.
3. Interactive entertainment.
4. Electronic commerce.

Access to remote information comes in many forms. It can be surfing the World Wide Web for information or just for fun. Information available includes the arts, business, cooking, government, health, history, hobbies, recreation, science, sports, travel, and many others. Fun comes in too many ways to mention, plus some ways that are better left unmentioned.

Many newspapers have gone on-line and can be personalized. For example, it is sometimes possible to tell a newspaper that you want everything about corrupt politicians, big fires, scandals involving celebrities, and epidemics, but no football, thank you. Sometimes it is even possible to have the selected articles downloaded to your hard disk while you sleep or printed on your printer just before breakfast. As this trend continues, it will cause massive unemployment among 12-year-old paperboys, but newspapers like it because distribution has always been the weakest link in the whole production chain.

The next step beyond newspapers (plus magazines and scientific journals) is the on-line digital library. Many professional organizations, such as the ACM (www.acm.org) and the IEEE Computer Society (www.computer.org), already have many journals and conference proceedings on-line. Other groups are following rapidly. Depending on the cost, size, and weight of book-sized notebook computers, printed books may become obsolete. Skeptics should take note of the effect the printing press had on the medieval illuminated manuscript.

All of the above applications involve interactions between a person and a remote database full of information. The second broad category of network use is person-to-person communication, basically the 21st century's answer to the 19th century's telephone. E-mail is already used on a daily basis by millions of people all over the world and its use is growing rapidly. It already routinely contains audio and video as well as text and pictures. Smell may take a while.

Any teenager worth his or her salt is addicted to **instant messaging**. This facility, derived from the UNIX *talk* program in use since around 1970, allows two people to type messages at each other in real time. A multiperson version of this idea is the **chat room**, in which a group of people can type messages for all to see.

Worldwide newsgroups, with discussions on every conceivable topic, are already commonplace among a select group of people, and this phenomenon will grow to include the population at large. These discussions, in which one person posts a message and all the other subscribers to the newsgroup can read it, run the gamut from humorous to impassioned. Unlike chat rooms, newsgroups are not real time and messages are saved so that when someone comes back from vacation, all messages that have been posted in the meanwhile are patiently waiting for reading.

Another type of person-to-person communication often goes by the name of **peer-to-peer** communication, to distinguish it from the client-server model (Parameswaran et al., 2001). In this form, individuals who form a loose group can communicate with others in the group, as shown in Fig. 1-3. Every person can, in principle, communicate with one or more other people; there is no fixed division into clients and servers.

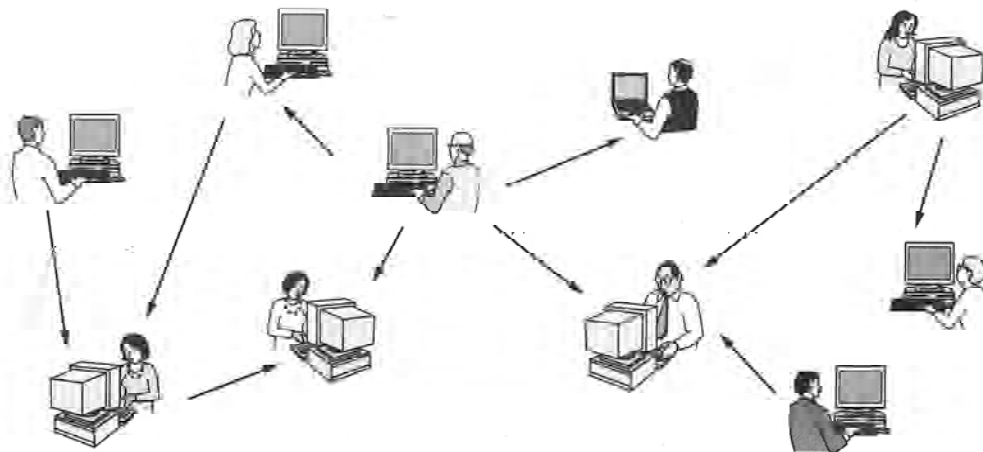


Figure 1-3. In a peer-to-peer system there are no fixed clients and servers.

Peer-to-peer communication really hit the big time around 2000 with a service called Napster, which at its peak had over 50 million music fans swapping music, in what was probably the biggest copyright infringement in all of recorded history (Lam and Tan, 2001; and Macedonia, 2000). The idea was fairly simple. Members registered the music they had on their hard disks in a central database maintained on the Napster server. If a member wanted a song, he checked the database to see who had it and went directly there to get it. By not actually keeping any music on its machines, Napster argued that it was not infringing anyone's copyright. The courts did not agree and shut it down.

However, the next generation of peer-to-peer systems eliminates the central database by having each user maintain his own database locally, as well as providing a list of other nearby people who are members of the system. A new user can then go to any existing member to see what he has and get a list of other members to inspect for more music and more names. This lookup process can be repeated indefinitely to build up a large local database of what is out there. It is an activity that would get tedious for people but is one at which computers excel.

Legal applications for peer-to-peer communication also exist. For example, fans sharing public domain music or sample tracks that new bands have released for publicity purposes, families sharing photos, movies, and genealogical information, and teenagers playing multiperson on-line games. In fact, one of the most popular Internet applications of all, e-mail, is inherently peer-to-peer. This form of communication is expected to grow considerably in the future.

Electronic crime is not restricted to copyright law. Another hot area is electronic gambling. Computers have been simulating things for decades. Why not simulate slot machines, roulette wheels, blackjack dealers, and more gambling equipment? Well, because it is illegal in a lot of places. The trouble is, gambling is legal in a lot of other places (England, for example) and casino owners there have grasped the potential for Internet gambling. What happens if the gambler and the casino are in different countries, with conflicting laws? Good question.

Other communication-oriented applications include using the Internet to carry telephone calls, video phone, and Internet radio, three rapidly growing areas. Another application is telelearning, meaning attending 8 A.M. classes without the inconvenience of having to get out of bed first. In the long run, the use of networks to enhance human-to-human communication may prove more important than any of the others.

Our third category is entertainment, which is a huge and growing industry. The killer application here (the one that may drive all the rest) is video on demand. A decade or so hence, it may be possible to select any movie or television program ever made, in any country, and have it displayed on your screen instantly. New films may become interactive, where the user is occasionally prompted for the story direction (should Macbeth murder Duncan or just bide his time?) with alternative scenarios provided for all cases. Live television may also become interactive, with the audience participating in quiz shows, choosing among contestants, and so on.

On the other hand, maybe the killer application will not be video on demand. Maybe it will be game playing. Already we have multiperson real-time simulation games, like hide-and-seek in a virtual dungeon, and flight simulators with the players on one team trying to shoot down the players on the opposing team. If games are played with goggles and three-dimensional real-time, photographic-quality moving images, we have a kind of worldwide shared virtual reality.

Our fourth category is electronic commerce in the broadest sense of the term. Home shopping is already popular and enables users to inspect the on-line cata-

logs of thousands of companies. Some of these catalogs will soon provide the ability to get an instant video on any product by just clicking on the product's name. After the customer buys a product electronically but cannot figure out how to use it, on-line technical support may be consulted.

Another area in which e-commerce is already happening is access to financial institutions. Many people already pay their bills, manage their bank accounts, and handle their investments electronically. This will surely grow as networks become more secure.

One area that virtually nobody foresaw is electronic flea markets (e-flea?). On-line auctions of second-hand goods have become a massive industry. Unlike traditional e-commerce, which follows the client-server model, on-line auctions are more of a peer-to-peer system, sort of consumer-to-consumer. Some of these forms of e-commerce have acquired cute little tags based on the fact that "to" and "2" are pronounced the same. The most popular ones are listed in Fig. 1-4.

Tag	Full name	Example
B2C	Business-to-consumer	Ordering books on-line
B2B	Business-to-business	Car manufacturer ordering tires from supplier
G2C	Government-to-consumer	Government distributing tax forms electronically
C2C	Consumer-to-consumer	Auctioning second-hand products on line
P2P	Peer-to-peer	File sharing

Figure 1-4. Some forms of e-commerce.

No doubt the range of uses of computer networks will grow rapidly in the future, and probably in ways no one can now foresee. After all, how many people in 1990 predicted that teenagers tediously typing short text messages on mobile phones while riding buses would be an immense money maker for telephone companies in 10 years? But short message service is very profitable.

Computer networks may become hugely important to people who are geographically challenged, giving them the same access to services as people living in the middle of a big city. Telelearning may radically affect education; universities may go national or international. Telemedicine is only now starting to catch on (e.g., remote patient monitoring) but may become much more important. But the killer application may be something mundane, like using the webcam in your refrigerator to see if you have to buy milk on the way home from work.

1.1.3 Mobile Users

Mobile computers, such as notebook computers and personal digital assistants (PDAs), are one of the fastest-growing segments of the computer industry. Many owners of these computers have desktop machines back at the office and want to be connected to their home base even when away from home or en route. Since

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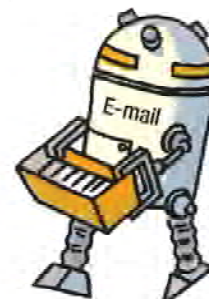
ANDREW S. TANENBAUM

The world's leading introduction to networking—fully updated for tomorrow's key technologies

Computer Networks, fourth edition, is the ideal introduction to today's networks—and *tomorrow's*. This classic bestseller has been thoroughly updated to reflect the newest and most important networking technologies with a special emphasis on wireless networking, including 802.11, Bluetooth™, broadband wireless, ad hoc networks, i-mode, and WAP. But fixed networks have not been ignored either, with coverage of ADSL, Internet over cable, gigabit Ethernet, peer-to-peer networks, NAT, and MPLS. And there is lots of new material on applications, including over 60 pages on the Web, plus Internet radio, Voice over IP, and video on demand. Finally, the coverage of network security has been revised and expanded to fill an entire chapter.

Author, educator, and researcher Andrew S. Tanenbaum, winner of the ACM Karl V. Karlstrom Outstanding Educator Award, carefully explains how networks work *on the inside*, from underlying hardware at the physical layer up through the top-level application layer. Tanenbaum covers all this and more:

- Physical layer (e.g., copper, fiber, wireless, satellites, and Internet over cable)
- Data link layer (e.g., protocol principles, protocol verification, HDLC, and PPP)
- MAC sublayer (e.g., gigabit Ethernet, 802.11, broadband wireless, and switching)
- Network layer (e.g., routing algorithms, congestion control, QoS, IPv4, and IPv6)
- Transport layer (e.g., socket programming, UDP, TCP, RTP, and network performance)
- Application layer (e.g., e-mail, the Web, PHP, wireless Web, MP3, and streaming audio)
- Network security (e.g., AES, RSA, quantum cryptography, IPsec, and Web security)



The book gives detailed descriptions of the principles associated with each layer and presents many examples drawn from the Internet and wireless networks.

About the Author

ANDREW S. TANENBAUM is Professor of Computer Science at Vrije Universiteit, Amsterdam, The Netherlands, and Scientific Director of ASCL, a Dutch graduate school established by leading universities throughout the Netherlands. He is also a Fellow of the IEEE and a Fellow of the ACM. Other books Tanenbaum has authored or co-authored include *Structured Computer Organization*, fourth edition; *Operating Systems: Design and Implementation*, second edition; *Modern Operating Systems*, second edition; and *Distributed Systems: Principles and Paradigms* (Prentice Hall).



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