COMPUTER NETWORKS

Sixth Edition

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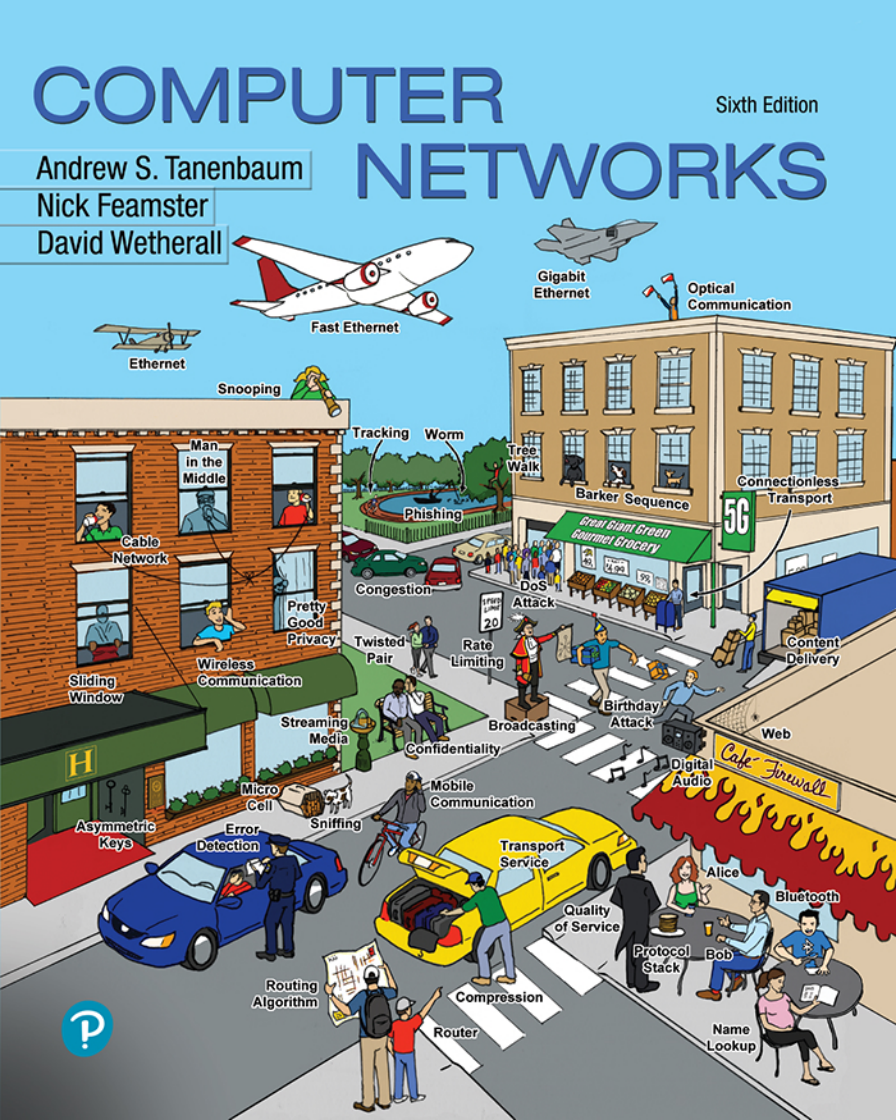

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Library of Congress Cataloging-in-Publication Data

Cataloging-in-Publication Data is available on file at the Library of Congress

ScoutAutomatedPrintCode

ISBN 10: 0-13-676405-3
ISBN 13: 978-0-13-676405-2

To Suzanne, Barbara, Daniel, Aron, Nathan, Marvin, Matilde, Olivia, and Mirte (AST)

To Marshini, Mila, and Kira (NF)

To Katrin, Lucy, and Pepper (DJW)

CONTENTS

PREFACE

This book is now in its sixth edition. Each edition has corresponded to a different phase in the way computer networks were used. When the first edition appeared in 1980, networks were an academic curiosity. When the second edition appeared in 1988, networks were used by universities and large businesses. When the third edition appeared in 1996, computer networks, especially the Internet, had become a daily reality for millions of people. By the fourth edition, in 2003, wireless networks and mobile computers had become commonplace for accessing the Web and the Internet. By the fifth edition, networks were about content distribution (especially videos using CDNs and peer-to-peer networks) and mobile phones. Now in the sixth edition, industry emphasis on is very high performance, with 5G cellular networks, 100-gigabit Ethernet, and 802.11ax WiFi at speeds up to 11 Gbps just around the corner.

New in the Sixth Edition

Among the many changes in this book, the most important one is the addition of Prof. Nick Feamster as a co-author. Prof. Feamster has a Ph.D. from M.I.T. and is now a full professor at the University of Chicago.

Another important change is that Chapter 8 (on security) has been very heavily modified by Prof. Herbert Bos of the Vrije Universiteit in Amsterdam. The focus has moved from cryptography to network security. The issues of hacking, DoS attacks and so much more is front-and-center in the news almost every day, so we are very grateful that Prof. Bos has redone the chapter to deal with these important issues in detail. The chapter discusses vulnerabilities, how to fix them, how hackers respond to the fixes, how the defenders react, and so on ad infinitum. The material on cryptography has been reduced somewhat to make room for the large amount of new material on network security.

Of course, the book also has many other changes to keep up with the ever-changing world of computer networks. A chapter-by-chapter list of the major changes follows.

Chapter 1 serves the same introductory function as in previous editions, but the contents have been revised and brought up to date. Specific updates including adding additional discussions on the Internet of Things and modern cellular architectures, including 4G and 5G networks. Much of the discussion on Internet policy has also been updated, particularly the discussion on net neutrality.

Chapter 2 has been updated to include discussion of more prevalent physical media in access networks, such as DOCSIS and fiber arhictectures. Treatment of modern cellular network architectures and technologies was added, and the section on satellite networks was also substantially updated. Emerging technologies such as virtualization were added, including discussions on mobile virtual network operators and cellular network slicing. The policy discussion was reorganized and updated to include discussion on policy questions in the wireless arena, such as spectrum.

Chapter 3 has been updated to include DOCSIS as a protocol example, as it is a widely used access technology. Much of the error correction codes are, of course, timeless.

Chapter 4 has been brought up to date, with new material on 40- and 100-gigabit Ethernet, 802.11.ac, 802.11ad, and 802.11ax. New material has been added on DOCSIS, explaining the MAC sublayer in cable networks. The material on 802.16 has been removed as it now appears that this technology is going to lose out to the cellular 4G and 5G technologies. The section on RFID has also been removed to make space for new material, but also because it was not directly network related.

Chapter 5 has been updated to clarify and modernize the discussions on congestion management. The sections on traffic management have been updated and clarified, and the discussions on traffic shaping and traffic engineering have been updated. The chapter includes an entirely new section on software-defined networking (SDN), including OpenFlow and programmable hardware (e.g., Tofino). The chapter also includes discussion on emerging applications of SDN, such as in-band network telemetry. Some of the discussion on IPv6 has also been updated.

Chapter 6 has been extensively edited to include new material on modern transport protocols, including TCP CUBIC, QUIC, and BBR. The material on performance measurement has been completely rewritten to focus on the measurement of throughput in computer networks, including an extensive discussion on the challenges of measuring access network throughout as speeds in access ISPs increase. The chapter also includes new material on measuring user quality of experience, an emerging area in performance measurement.

Chapter 7 has been heavily edited. Over 60 pages of material that is no longer relevant to a book on computer networks has been removed. The material on DNS has been almost completely rewritten to reflect modern developments in DNS, including the ongoing trends to encrypt DNS and generally improve its privacy characteristics. Emerging protocols such as DNS-over-HTTPS and other privacy-preserving techniques for DNS are discussed. The discussion of the Web has been extensively updated, to reflect the increasing deployment of encryption on the Web,

as well as extensive privacy issues (e.g., tracking) that are now pervasive on the Web. The chapter includes a completely new section on Web privacy, more extensive discussions of modern content delivery technology (e.g., content delivery networks), and an expanded discussion on peer-to-peer networks. The section on the evolution of the Internet has also been edited to reflect trends towards distributed cloud services.

Chapter 8 has been completely overhauled. In previous editions, the focus of the security chapter was almost exclusively on information security by means of cryptography. However, cryptography is only one aspect of network security and if we look at security incidents in practice, it is generally not the aspect where the problems are. To remedy this, we added new content on security principles, fundamental attack techniques, defenses, and a wide range of systems-related security issues. Moreover, we updated the existing sections by dropping some encryption techniques that are now obsolete and introducing more modern versions of protocols and standards.

Chapter 9 contains a renewed list of suggested readings and a comprehensive bibliography.

In addition, dozens of new exercises and dozens of new references have been added.

List of Acronyms

Computer books are full of acronyms. This one is no exception. By the time you are completely finished reading this one, the following should ring a bell: AES, AMI, ARP, ARQ, ASK, BGP, BSC, CCK, CDM, CDN, CRL, DCF, DES, DIS, DMT, DMZ, DNS, EAP, ECN, EDE, EPC, FDD, FDM, FEC, FSK, GEO, GSM, HFC, HLR, HLS, HSS, IAB, IDS, IGP, IKE, IPS, ISM, ISO, ISP, ITU, IXC, IXP, KDC, LAN, LCP, LEC, LEO, LER, LLD, LSR, LTE, MAN, MEO, MFJ, MGW, MIC, MME, MPD, MSC, MSS, MTU, NAP, NAT, NAV, NCP, NFC, NIC, NID, NRZ, ONF, OSI, PAR, PCF, PCM, PCS, PGP, PHP, PIM, PKI, PON, POP, PPP, PSK, RAS, RCP, RED, RIP, RMT, RNC, RPC, RPR, RTO, RTP, SCO, SDH, SDN, SIP, SLA, SNR, SPE, SSL, TCG, TCM, TCP, TDM, TLS, TPM, UDP, URL, USB, UTP, UWB, VLR, VPN, W3C, WAF, WAN, WDM, WEP, WFQ and WPA. But don't worry. Each will appear in **boldface type** and be carefully defined before it is used. As a fun test, see how many you can identify *before* reading the book, write the number in the margin, then try again *after* reading the book.

Instructors' Resource Materials

The following protected instructors' resource materials are available on the publisher's Web site at *www.pearsonhighered.com/tanenbaum*. For a username and password, please contact your local Pearson representative.

- Solutions manual
- PowerPoint lecture slides

Students' Resource Materials

Resources for students are available through the open-access Companion Web site link on *www.pearsonhighered.com/tanenbaum*, including

- Figures, tables, and programs from the book
- Steganography demo
- Protocol simulators

In addition, the authors have a Web site with other resources for students at *www.computernetworksbook.com*.

Acknowledgements

Many people helped us during the course of the sixth edition. We would especially like to thank Phyllis Davis (St. Louis Community College), Farah Kandah (University of Tennessee, Chattanooga), Jason Livingood (Comcast), Louise Moser (University of California, Santa Barbara), Jennifer Rexford (Princeton), Paul Schmitt (Princeton), Doug Sicker (CMU), Wenye Wang (North Carolina State University), and Greg White (Cable Labs).

Some of Prof. Tanenbaum's students have given valuable feedback on the manuscript, including: Ece Doganer, Yael Goede, Bruno Hoevelaken, Elena Ibi, Oskar Klonowski, Johanna Sänger, Theresa Schantz, Karlis Svilans, Mascha van der Marel, Anthony Wilkes, for providing ideas and feedback.

Jesse Donkervliet (Vrije Universiteit) thought of many new end-of-chapter exercises to challenge the reader.

Paul Nagin (Chimborazo Publishing, Inc.) produced the Power Point slides for instructors.

Our editor at Pearson, Tracy Johnson, was her usual helpful self in many ways large and small. Without her advice, drive, and persistence, this edition might never have happened. Thank you Tracy. We really appreciate your help.

Finally, we come to the most important people. Suzanne has been through this 23 times now and still has endless patience and love. Barbara and Marvin now know the difference between good textbooks and bad ones and are always an inspiration to produce good ones. Daniel and Matilde are wonderful additions to our family. Aron, Nathan, Olivia, and Mirte probably aren't going to read this edition, but they inspire me and make me hopeful about the future (AST). Marshini, Mila, and Kira: My favorite network is the one we have built together. Thank you for your support and love (NF). Katrin and Lucy provided endless support and always managed to keep a smile on my face. Thank you (DJW).

ANDREW S. TANENBAUM

NICK FEAMSTER

DAVID J. WETHERALL

1

INTRODUCTION

Each of the past three centuries was dominated by a single new technology. The 18th century was the era of the great mechanical systems accompanying the Industrial Revolution. The 19th century was the age of the steam engine. During the 20th century, the key technology was information gathering, processing, and distribution. Among other developments, we saw the deployment of worldwide telephone networks, the invention of radio and television, the birth and unprecedented growth of the computer industry, the launching of communication satellites, and, of course, the Internet. Who knows what miracles the 21st century will bring?

As a result of this rapid technological progress, these areas are rapidly converging in the 21st century, and the differences between collecting, transporting, storing, and processing information are quickly disappearing. Organizations with hundreds of offices spread over a wide geographical area routinely expect to be able to examine the current status of even their most remote outpost at the push of a button. As our ability to gather, process, and distribute information grows, the demand for more sophisticated information processing grows even faster.

1.1 USES OF COMPUTER NETWORKS

Although the computing industry is still young compared to other technical industries such as automobiles and air transportation, computers have made spectacular progress in a short time. During the first two decades of their existence,

computer systems were highly centralized, usually within a single room. Often, this room had glass windows, through which visitors could gawk at the great electronic wonder inside. A medium-sized company or university might have had one or two computers, while large institutions had at most a few dozen. The idea that within fifty years vastly more powerful computers smaller than postage stamps would be mass produced by the billions was science fiction.

The convergence of computers and communications has had a profound influence on the organization of computer systems. The once-dominant concept of the "computer center" as a room with a single large computer to which users bring their work for processing is now obsolete (although data centers holding hundreds of thousands of Internet servers are common). The old model of a single computer serving all of the organization's computational needs has been replaced by one in which a large number of separate but interconnected computers do the job. These systems are called **computer networks**. The design and organization of these networks are the subjects of this book.

Throughout the book, we will use the term "computer network" to mean a collection of interconnected, autonomous computing devices. Two computers are said to be interconnected if they can exchange information. Interconnection can take place over a variety of transmission media including copper wire, fiber optic cable, and radio waves (e.g., microwave, infrared, communication satellites). Networks come in many sizes, shapes, and forms, as we will explore throughout the book. They are usually connected to make larger networks, with the **Internet** being the most well-known example of a network of networks.

1.1.1 Access to Information

Access to information comes in many forms. A common method of accessing information via the Internet is using a Web browser, which allows a user to retrieve information from various Web sites, including increasingly popular social media sites. Mobile applications on smartphones now also allow users to access remote information. Topics include 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.

News organizations have largely migrated online, with some even ceasing print operations entirely. Access to information, including the news, is increasingly personalizable. Some online publications even allow you to tell them that you are interested in corrupt politicians, big fires, scandals involving celebrities, and epidemics, but no football, thank you. This trend certainly threatens the employment of 12-year-old paperboys, but online distribution has allowed the distribution of news to reach far larger and broader audiences.

Increasingly, news is also being curated by social media platforms, where users can post and share news content from a variety of sources, and where the news that any given user sees is prioritized and personalized based on both explicit user

preferences and complex machine learning algorithms that predict user preferences based on the user's history. Online publishing and content curation on social media platforms supports a funding model that depends largely on highly targeted behavioral advertising, which necessarily implies gathering data about the behavior of individual users. This information has sometimes been misused.

Online digital libraries and retail sites now host digital versions of content ranging from academic journals to books. Many professional organizations, such as the ACM (*www.acm.org*) and the IEEE Computer Society (*www.computer.org*), already have all their journals and conference proceedings online. Electronic book readers and online libraries may someday make printed books obsolete. Skeptics should take note of the effect the printing press had on the medieval illuminated manuscript.

Much information on the Internet is accessed using a client-server model, where a client explicitly requests information from a server that hosts that information, as illustrated in Fig. 1-1.

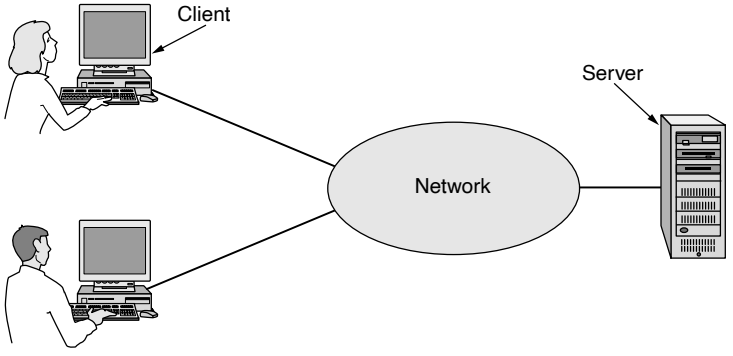

Figure 1-1. A network with two clients and one server.

The **client-server model** is widely used and forms the basis of much network usage. The most popular realization is that of a **Web application**, where a server generates Web pages based on its database in response to client requests that may update the database. The client-server model is applicable not only when the client and server are both in the same building (and 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 (hundreds or thousands) of clients simultaneously.

If we look at the client-server model, to a first approximation we see that two processes (running programs) 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 server 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.

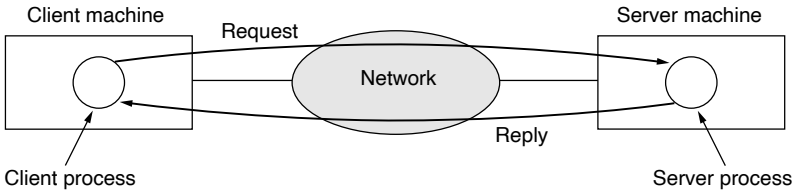

Figure 1-2. The client-server model involves requests and replies.

Another popular model for accessing information is **peer-to-peer** communication (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.

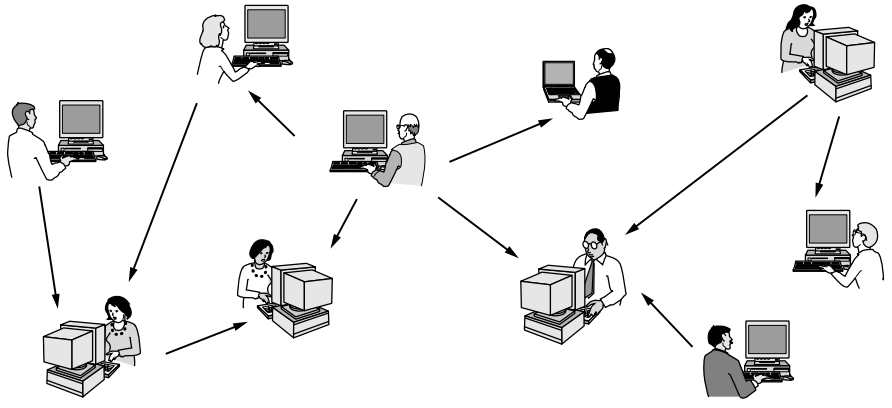

Figure 1-3. In a peer-to-peer system, there are no fixed clients and servers.

Many peer-to-peer systems, such as BitTorrent (Cohen, 2003), do not have a central database of content. Instead, each user maintains a local database of content, as well as a list of other members of the system. A new user can then go to any existing member to see what he has and get the names of other members to inspect for more content 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 computers excel at it.

Peer-to-peer communication is often used to share music and videos. It really hit the big time around 2000 with a music sharing service called Napster, which was shut down after a monumental copyright infringement case (Lam and Tan, 2001; and Macedonia, 2000). Legal applications for peer-to-peer communication now exist. These include fans sharing public domain music, families sharing photos and movies, and users downloading public software packages. In fact, one of the most popular Internet applications of all, email, is (conceptually) peer-to-peer. This form of communication is likely to grow considerably in the future.

1.1.2 Person-to-Person Communication

Person-to-person communication is the 21st century's answer to the 19th century's telephone. Email 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.

Many Internet users now rely on some form of **instant messaging** to communicate with other people on the Internet. 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. There are also multi-person messaging services too, such as the **Twitter** service, which lets people send short messages (possibly including video) called "tweets" to their circle of friends or other followers or the whole world.

The Internet can be used by applications to carry audio (e.g., Internet radio stations, streaming music services) and video (e.g., Netflix, YouTube). Besides being an inexpensive way to communicate with your distant friends, these applications can provide rich experiences such as distance learning, 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. It 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.

Between person-to-person communications and accessing information are **social network** applications. In these applications, the flow of information is driven by the relationships that people declare between each other. One of the most popular social networking sites is **Facebook**. It lets people create and update their personal profiles and shares the updates with other people who they have declared to be their friends. Other social networking applications can make introductions via friends of friends, send news messages to friends, such as Twitter above, and much more.

Even more loosely, groups of people can work together to create content. A **wiki**, for example, is a collaborative Web site that the members of a community edit. The most famous wiki is the **Wikipedia**, an encyclopedia anyone can read or edit, but there are thousands of other wikis.

1.1.3 Electronic Commerce

Online shopping is already popular; users can browse the online catalogs of thousands of companies and have products shipped right to their doorsteps. After the customer buys a product electronically but cannot figure out how to use it, online technical support may be consulted.

Another area in which e-commerce is widely used is access to financial institutions. Many people already pay their bills, manage their bank accounts, and even handle their investments electronically. Financial technology or "fintech" applications allow users to conduct a wide variety of financial transactions online, including transferring money between bank accounts, or even between friends.

Online auctions of second-hand goods have become a massive industry. Unlike traditional e-commerce, which follows the client-server model, online auctions are peer-to-peer in the sense that consumers can act as both buyers and sellers, although there is a central server that holds the database of products for sale.

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 online
B2B	Business-to-business	Car manufacturer ordering tires from a supplier
G2C	Government-to-consumer	Government distributing tax forms electronically
C2C	Consumer-to-consumer	Auctioning second-hand products online
P2P	Peer-to-peer	Music or file sharing; Skype

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

1.1.4 Entertainment

Our fourth category is entertainment. This has made huge strides in the home in recent years, with the distribution of music, radio and television programs, and movies over the Internet beginning to rival that of traditional mechanisms. Users can find, buy, and download MP3 songs and high-definition movies and add them to their personal collection. TV shows now reach many homes via **IPTV** (**IP Television**) systems that are based on IP technology instead of cable TV or radio transmissions. Media streaming applications let users tune to Internet radio stations or watch recent episodes of their favorite TV shows or movies. Naturally, all of this content can be moved around your house between different devices, displays, and speakers, usually via a wireless network.

Soon, it may be possible to search for any movie or television program ever made, in any country, and have it be displayed on your screen instantly. New films

may become interactive, where the user is occasionally prompted for the story direction (should Macbeth murder the king 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.

Another form of entertainment is game playing. Already we have multi-person 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. Virtual worlds provide a persistent setting in which thousands of users can experience a shared reality with three-dimensional graphics.

1.1.5 The Internet of Things

Ubiquitous computing entails computing that is embedded in everyday life, as in the vision of Mark Weiser (1991). Many homes are already wired with security systems that include door and window sensors. Also, there are many more sensors that can be folded into a smart home monitor, such as energy consumption. Smart electricity, gas, and water meters report usage over the network. This functionality saves the company money as there is then no need to send people to read the meters. Smoke detectors can call the fire department instead of just making a big noise (which has little value if no one is home). Smart refrigerators could order more milk when it is almost gone. As the cost of sensing and communication drops, more and more measurement and reporting will be done with networks. This ongoing revolution, often referred to as the **IoT** (**Internet of Things**), is poised to connect just about every electronic device we purchase to the Internet.

Increasingly, consumer electronic devices are networked. For example, some high-end cameras already have a wireless network capability and use it to send photos to a nearby display for viewing. Professional sports photographers can also send their photos to their editors in real-time, first wirelessly to an access point then over the Internet. Devices such as televisions that plug into the wall can use **power-line networks** to send information throughout the house over the wires that carry electricity. It may not be very surprising to have these objects on the network, but objects that we do not think of as computers may sense and communicate information too. For example, your shower may record water usage, give you visual feedback while you lather up, and report to a home environmental monitoring application when you are done to help save on your water bill.

1.2 TYPES OF COMPUTER NETWORKS

There are many distinct types of computer networks. This section provides an overview of a few of these networks, including those we commonly use to access the Internet (mobile and broadband access networks); those that house the data and

applications we use every day (data-center networks); those that connect access networks to data centers (transit networks); and those that we use on a campus, office building, or other organization (enterprise networks).

1.2.1 Broadband Access Networks

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. People initially bought computers for word processing and games. Now the prevailing reason to buy a home computer is to get Internet access. Also, many consumer electronic devices, such as set-top boxes, game consoles, television sets, and even door locks, come with embedded computers that access computer networks, especially wireless networks. Home networks are broadly used for entertainment, including listening to, looking at, and creating music, photos, and videos.

Internet access provides home users with **connectivity** to remote computers. As with companies, home users can access information, communicate with other people, and buy products and services. The main benefit now comes from connecting these devices to other destinations outside of the home. Bob Metcalfe, the inventor of Ethernet, hypothesized that the value of a network is proportional to the square of the number of users because this is roughly the number of different connections that may be made (Gilder, 1993). This hypothesis is known as "Metcalfe's law." It helps to explain how the tremendous popularity of the Internet comes from its size.

Today, broadband access networks are proliferating. In many parts of the world, broadband access is delivered to homes through copper (e.g., telephone lines), coaxial cable (e.g., cable), or optical fiber. The speeds of broadband Internet access continue to increase as well, with many broadband access providers in developed countries delivering a gigabit per second to individual homes. In some parts of the world, particularly in developing regions, the predominant mode of Internet access is mobile.

1.2.2 Mobile and Wireless Access Networks

Mobile computers, such as laptops, tablets, and smartphones, are one of the fastest-growing segments of the computer industry. Their sales have already overtaken those of desktop computers. Why would anyone want one? People on the go often want to use their mobile devices to read and send email, tweet, watch movies, download music, play games, look at maps, or simply to surf the Web for information or fun. They want to do all of the things they do at home and in the office. Naturally, they want to do them from anywhere on land, sea, or in the air.

Connectivity to the Internet enables many of these mobile uses. Since having a wired connection is impossible in cars, boats, and airplanes, there is a lot of interest in wireless networks. Cellular networks operated by telephone companies are one familiar kind of wireless network that blankets us with coverage for mobile phones. Wireless **hotspots** based on the 802.11 standard are another kind of wireless network for mobile computers and portable devices such as phones and tablets. They have sprung up everywhere that people go, resulting in a patchwork of coverage at cafes, hotels, airports, schools, trains, and planes. Anyone with a mobile device and a wireless modem can just turn on their computer and be connected to the Internet through the hotspot as though the computer were plugged into a wired network.

Wireless networks are of great value to fleets of trucks, taxis, delivery vehicles, and repair-persons for keeping in contact with their home base. For example, in many cities, taxi drivers are independent businessmen, rather than being employees of a taxi company. In some of these cities, the taxis have a display the driver can see. When a customer calls up, a central dispatcher types in the pickup and destination points. This information is displayed on the drivers' displays and a beep sounds. The first driver to hit a button on the display gets the call. The rise of mobile and wireless networking has also led to a revolution in ground transportation itself, with the "sharing economy" allowing drivers to use their on phones as a dispatch device, as with ride-sharing companies such as Uber and Lyft.

Wireless networks are also important to the military. If you have to be able to fight a war anywhere on Earth at short notice, counting on using the local networking infrastructure is probably not a good idea. It is better to bring your own.

Although wireless networking and mobile computing are often related, they are not identical, as Fig. 1-5 shows. Here, we see a distinction between **fixed wireless** and **mobile wireless** networks. Even notebook computers are sometimes wired. For example, if a traveler plugs a laptop computer into the wired network jack in a hotel room, he has mobility without a wireless network. The growing pervasiveness of wireless networks is making this situation increasingly rare, although for high performance, wired networks are always better.

Wireless	Mobile	Typical applications
No	No	Desktop computers in offices
No	Yes	A laptop computer used in a hotel room
Yes	No	Networks in unwired buildings
Yes	Yes	Store inventory with a handheld computer

Figure 1-5. Combinations of wireless networks and mobile computing.

Conversely, some wireless computers are not mobile. In people's homes, and in offices or hotels that lack suitable cabling, it can be more convenient to connect desktop computers or media players wirelessly than to install wires. Installing a