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Computer Networking

A TOP-DOWN APPROACH

SEVENTH EDITION

PEARSON

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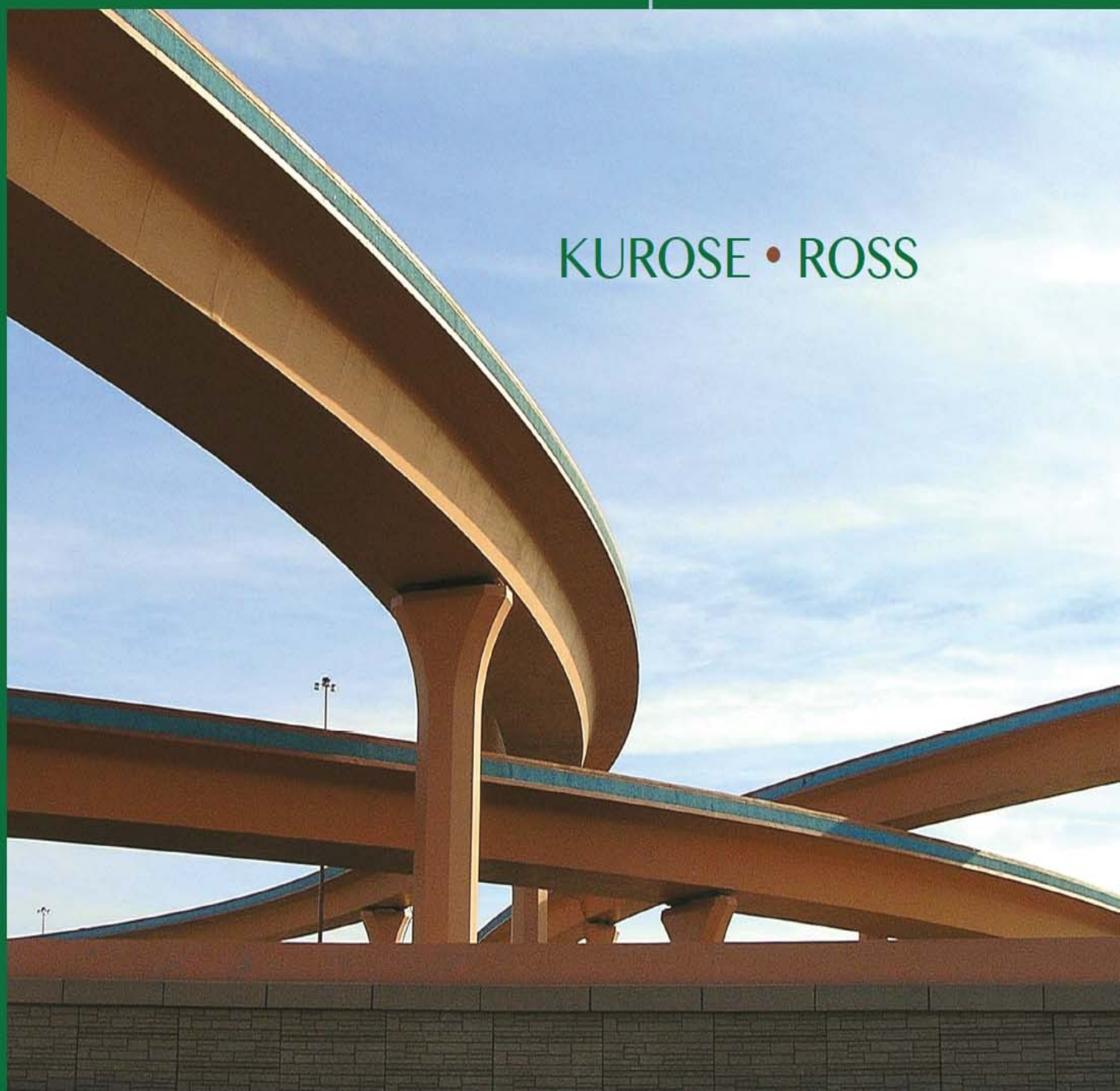

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Dr. Kurose has received a number of recognitions for his educational activities including Outstanding Teacher Awards from the National Technological University (eight times), the University of Massachusetts, and the Northeast Association of Graduate Schools. He received the IEEE Taylor Booth Education Medal and was recognized for his leadership of Massachusetts' Commonwealth Information Technology Initiative. He has won several conference best paper awards and received the IEEE Infocom Achievement Award and the ACM Sigcomm Test of Time Award.

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

Keith Ross

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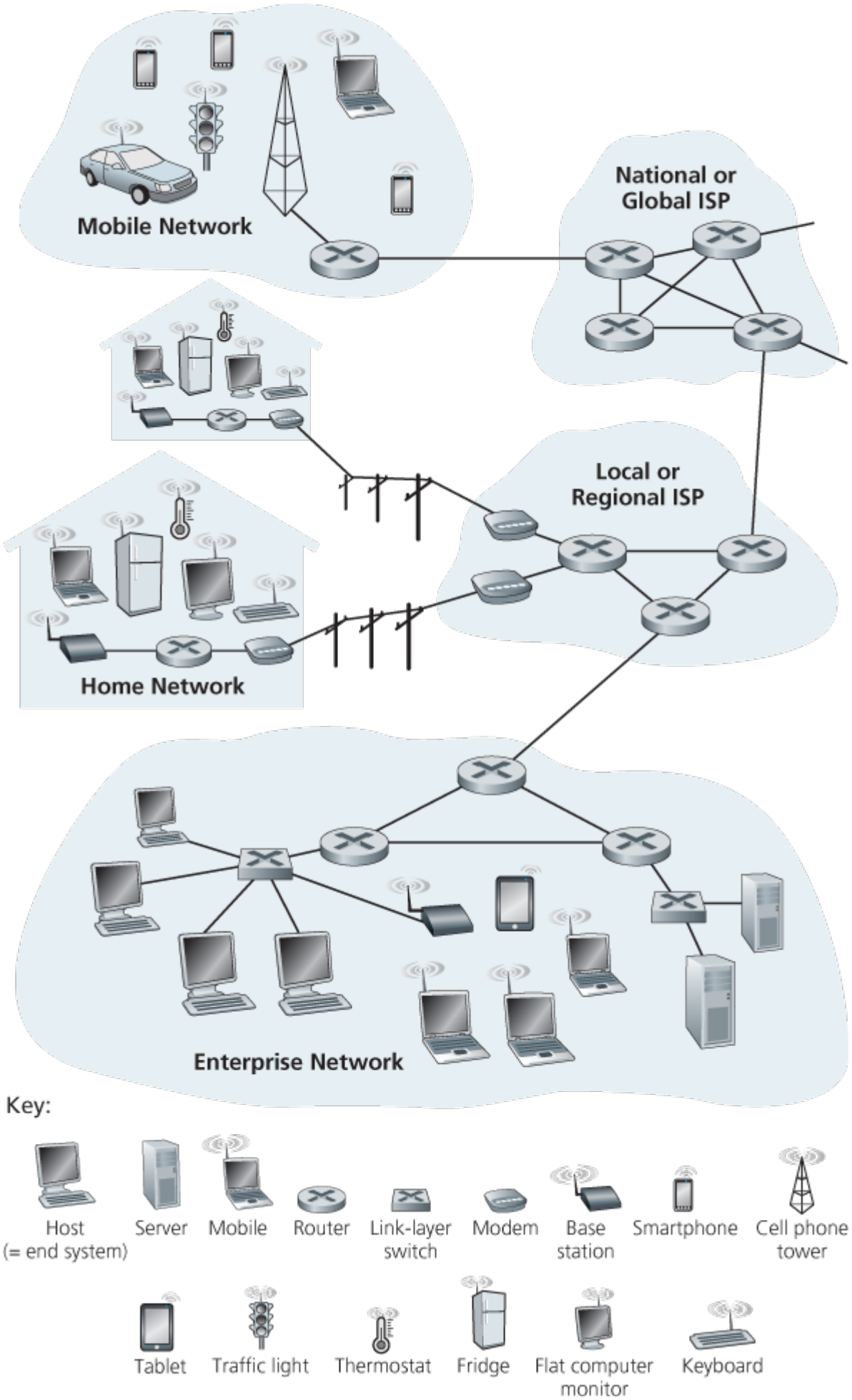

Figure 1.1 Some pieces of the Internet

End systems are connected together by a network of **communication links** and **packet switches**. We'll see in **Section 1.2** that there are many types of communication links, which are made up of

Now that we've got a bit of a feel for what the Internet is, let's consider another important buzzword in computer networking: *protocol*. What is a protocol? What does a protocol do?

A Human Analogy

It is probably easiest to understand the notion of a computer network protocol by first considering some human analogies, since we humans execute protocols all of the time. Consider what you do when you want to ask someone for the time of day. A typical exchange is shown in **Figure 1.2**. Human protocol (or good manners, at least) dictates that one first offer a greeting (the first "Hi" in **Figure 1.2**) to initiate communication with someone else. The typical response to a "Hi" is a returned "Hi" message. Implicitly, one then takes a cordial "Hi" response as an indication that one can proceed and ask for the time of day. A different response to the initial "Hi" (such as "Don't bother me!" or "I don't speak English," or some unprintable reply) might

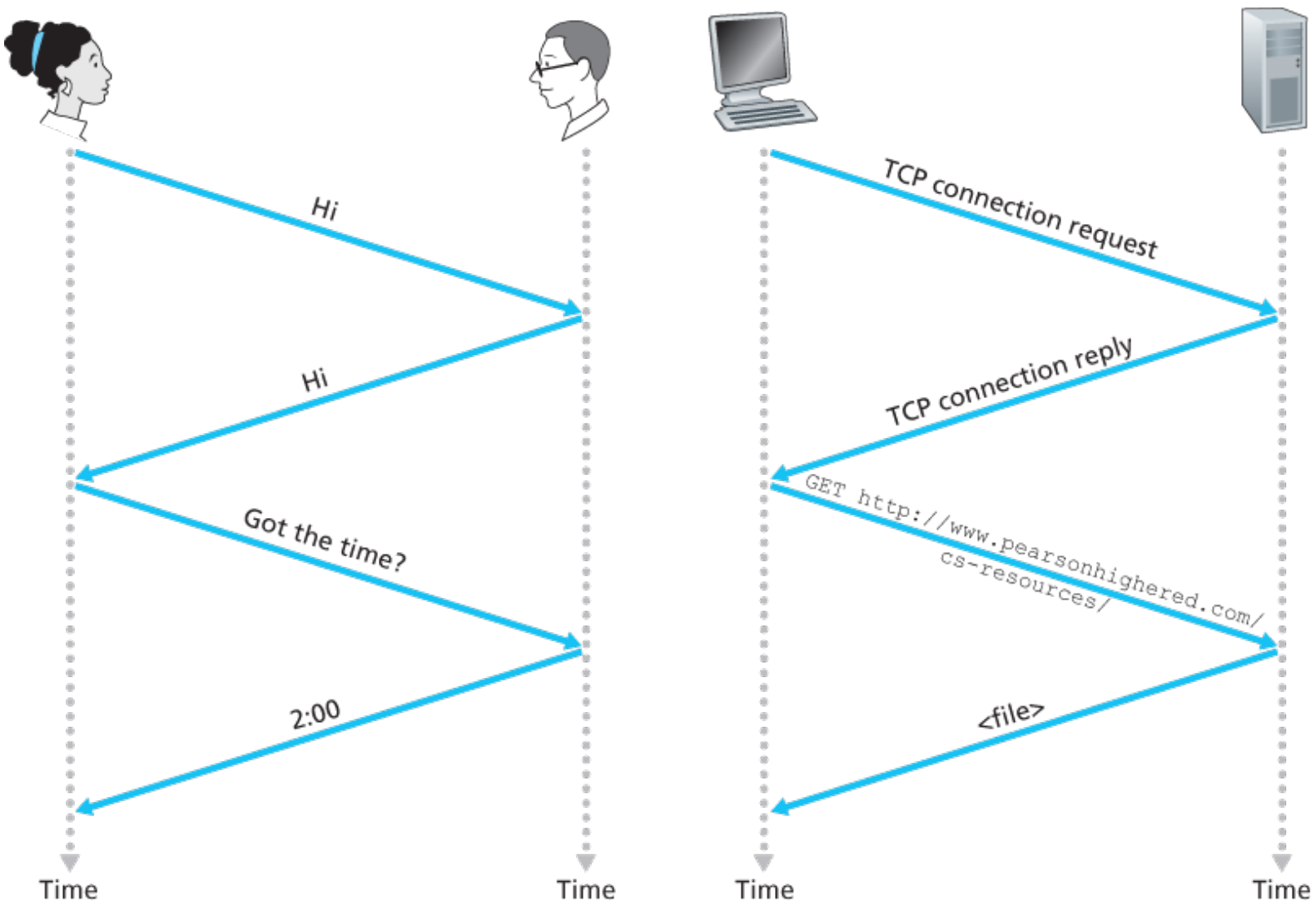

Figure 1.2 A human protocol and a computer network protocol

indicate an unwillingness or inability to communicate. In this case, the human protocol would be not to ask for the time of day. Sometimes one gets no response at all to a question, in which case one typically gives up asking that person for the time. Note that in our human protocol, *there are specific messages*

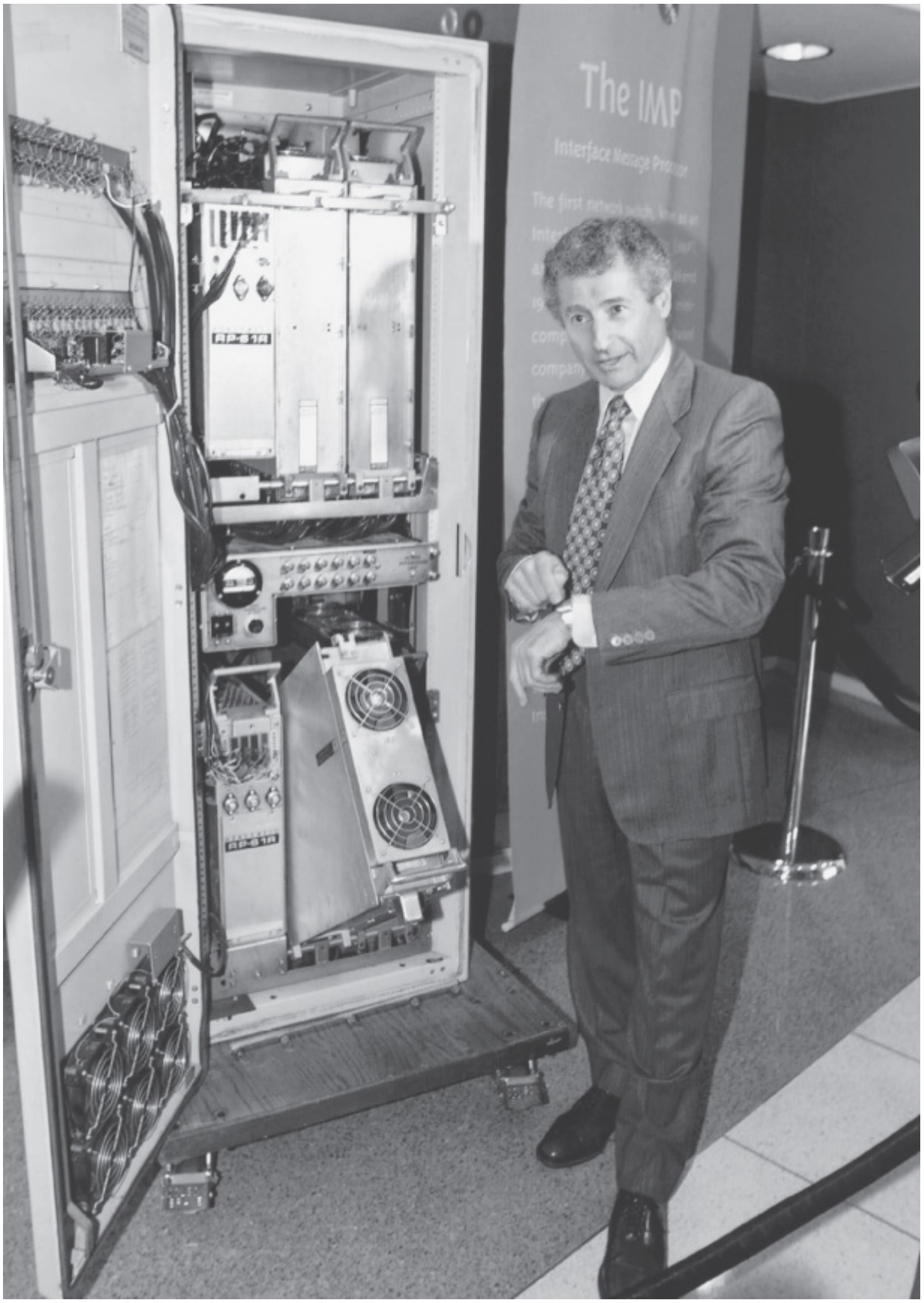

Figure 1.26 An early packet switch

and packet-radio networks **[Kahn 1978]**; Telenet, a BBN commercial packet-switching network based on ARPAnet technology; Cyclades, a French packet-switching network pioneered by Louis Pouzin **[Think 2012]**; Time-sharing networks such as Tymnet and the GE Information Services network, among others, in the late 1960s and early 1970s **[Schwartz 1977]**; IBM's SNA (1969–1974), which paralleled the ARPAnet work **[Schwartz 1977]**.

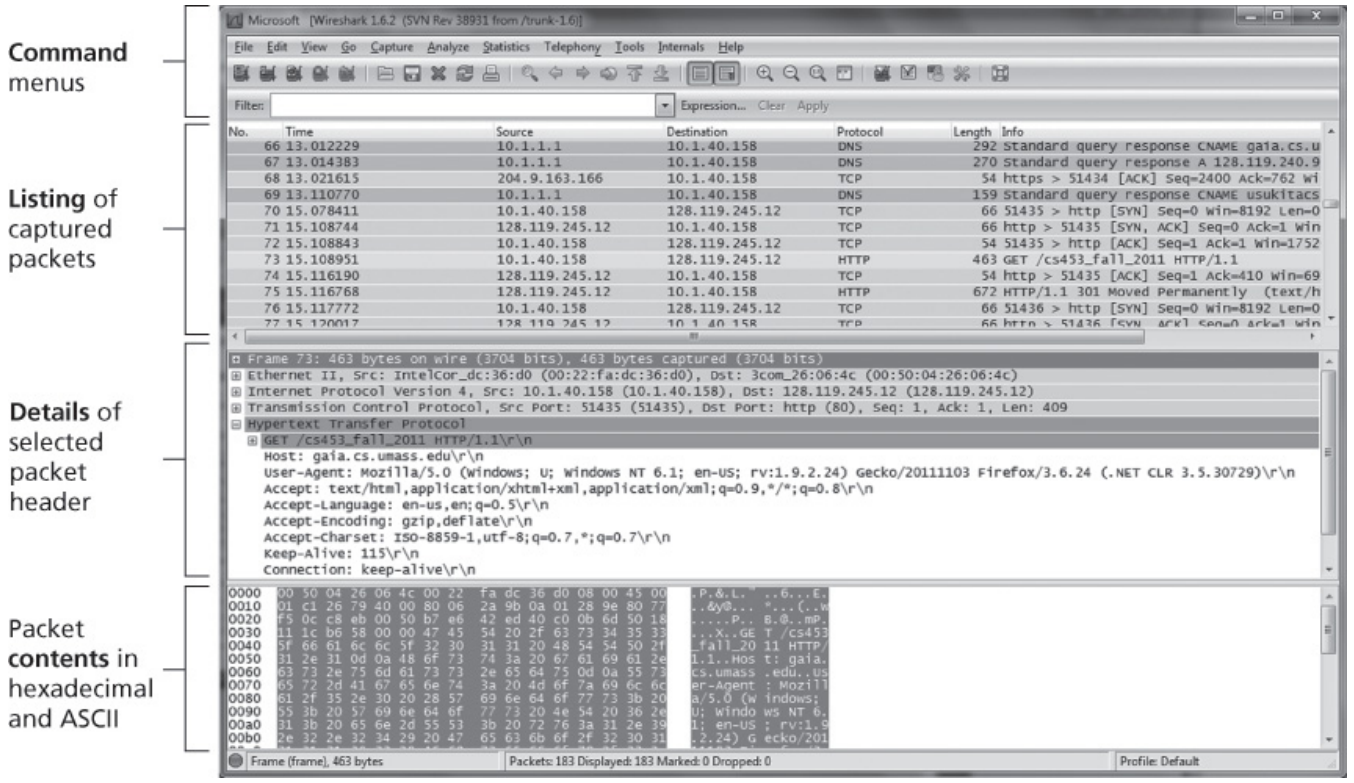

Figure 1.28 A Wireshark screenshot (Wireshark screenshot reprinted by permission of the Wireshark Foundation.)

Throughout the textbook, you will find Wireshark labs that allow you to explore a number of the protocols studied in the chapter. In this first Wireshark lab, you'll obtain and install a copy of Wireshark, access a Web site, and capture and examine the protocol messages being exchanged between your Web browser and the Web server.

You can find full details about this first Wireshark lab (including instructions about how to obtain and install Wireshark) at the Web site **http://www.pearsonhighered.com/cs-resources/**.

AN INTERVIEW WITH…

Leonard Kleinrock

Leonard Kleinrock is a professor of computer science at the University of California, Los Angeles. In 1969, his computer at UCLA became the first node of the Internet. His creation of packet-switching principles in 1961 became the technology behind the Internet. He received his B.E.E. from the City College of New York (CCNY) and his masters and PhD in electrical engineering from MIT.

address, similar to the return address with ordinary postal mail. With this source address information, the server now knows to where it should direct its reply.

```
modifiedMessage = message.decode().upper()
```

This line is the heart of our simple application. It takes the line sent by the client and, after converting the message to a string, uses the method `upper()` to capitalize it.

```
serverSocket.sendto(modifiedMessage.encode(), clientAddress)
```

This last line attaches the client's address (IP address and port number) to the capitalized message (after converting the string to bytes), and sends the resulting packet into the server's socket. (As mentioned earlier, the server address is also attached to the packet, although this is done automatically rather than explicitly by the code.) The Internet will then deliver the packet to this client address. After the server sends the packet, it remains in the while loop, waiting for another UDP packet to arrive (from any client running on any host).

To test the pair of programs, you run UDPClient.py on one host and UDPServer.py on another host. Be sure to include the proper hostname or IP address of the server in UDPClient.py. Next, you execute UDPServer.py, the compiled server program, in the server host. This creates a process in the server that idles until it is contacted by some client. Then you execute UDPClient.py, the compiled client program, in the client. This creates a process in the client. Finally, to use the application at the client, you type a sentence followed by a carriage return.

To develop your own UDP client-server application, you can begin by slightly modifying the client or server programs. For example, instead of converting all the letters to uppercase, the server could count the number of times the letter *s* appears and return this number. Or you can modify the client so that after receiving a capitalized sentence, the user can continue to send more sentences to the server.

2.7.2 Socket Programming with TCP

Unlike UDP, TCP is a connection-oriented protocol. This means that before the client and server can start to send data to each other, they first need to handshake and establish a TCP connection. One end of the TCP connection is attached to the client socket and the other end is attached to a server socket. When creating the TCP connection, we associate with it the client socket address (IP address and port

Chapter 4 The Network Layer: Data Plane

We learned in the previous chapter that the transport layer provides various forms of process-to-process communication by relying on the network layer's host-to-host communication service. We also learned that the transport layer does so without any knowledge about how the network layer actually implements this service. So perhaps you're now wondering, what's under the hood of the host-to-host communication service, what makes it tick?

In this chapter and the next, we'll learn exactly how the network layer can provide its host-to-host communication service. We'll see that unlike the transport and application layers, *there is a piece of the network layer in each and every host and router in the network.* Because of this, network-layer protocols are among the most challenging (and therefore among the most interesting!) in the protocol stack.

Since the network layer is arguably the most complex layer in the protocol stack, we'll have a lot of ground to cover here. Indeed, there is *so* much to cover that we cover the network layer in two chapters. We'll see that the network layer can be decomposed into two interacting parts, the **data plane** and the **control plane**. In **Chapter 4**, we'll first cover the data plane functions of the network layer—the *per-router* functions in the network layer that determine how a datagram (that is, a network-layer packet) arriving on one of a router's input links is forwarded to one of that router's output links. We'll cover both traditional IP forwarding (where forwarding is based on a datagram's destination address) and generalized forwarding (where forwarding and other functions may be performed using values in several different fields in the datagram's header). We'll study the IPv4 and IPv6 protocols and addressing in detail. In **Chapter 5**, we'll cover the control plane functions of the network layer—the *network-wide* logic that controls how a datagram is routed among routers along an end-to-end path from the source host to the destination host. We'll cover routing algorithms, as well as routing protocols, such as OSPF and BGP, that are in widespread use in today's Internet. Traditionally, these control-plane routing protocols and data-plane forwarding functions have been implemented together, monolithically, within a router. Software-defined networking (SDN) explicitly separates the data plane and control plane by implementing these control plane functions as a separate service, typically in a remote "controller." We'll also cover SDN controllers in **Chapter 5**.

This distinction between data-plane and control-plane functions in the network layer is an important concept to keep in mind as you learn about the network layer—it will help structure your thinking about

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