TCP/IP Illustrated, Volume 1

The Protocols

SECOND EDITION

Kevin R. Fall
W. Richard Stevens

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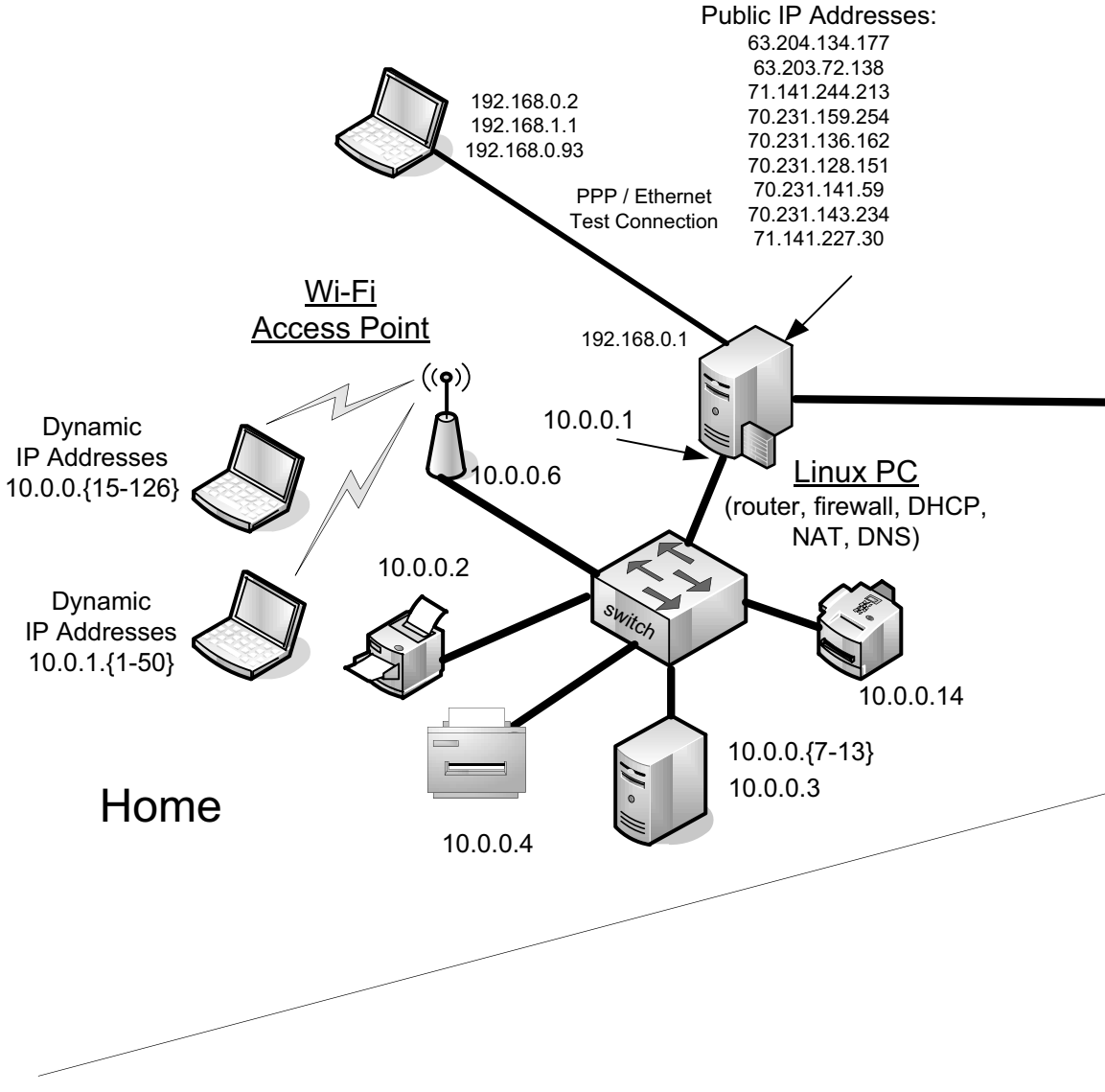
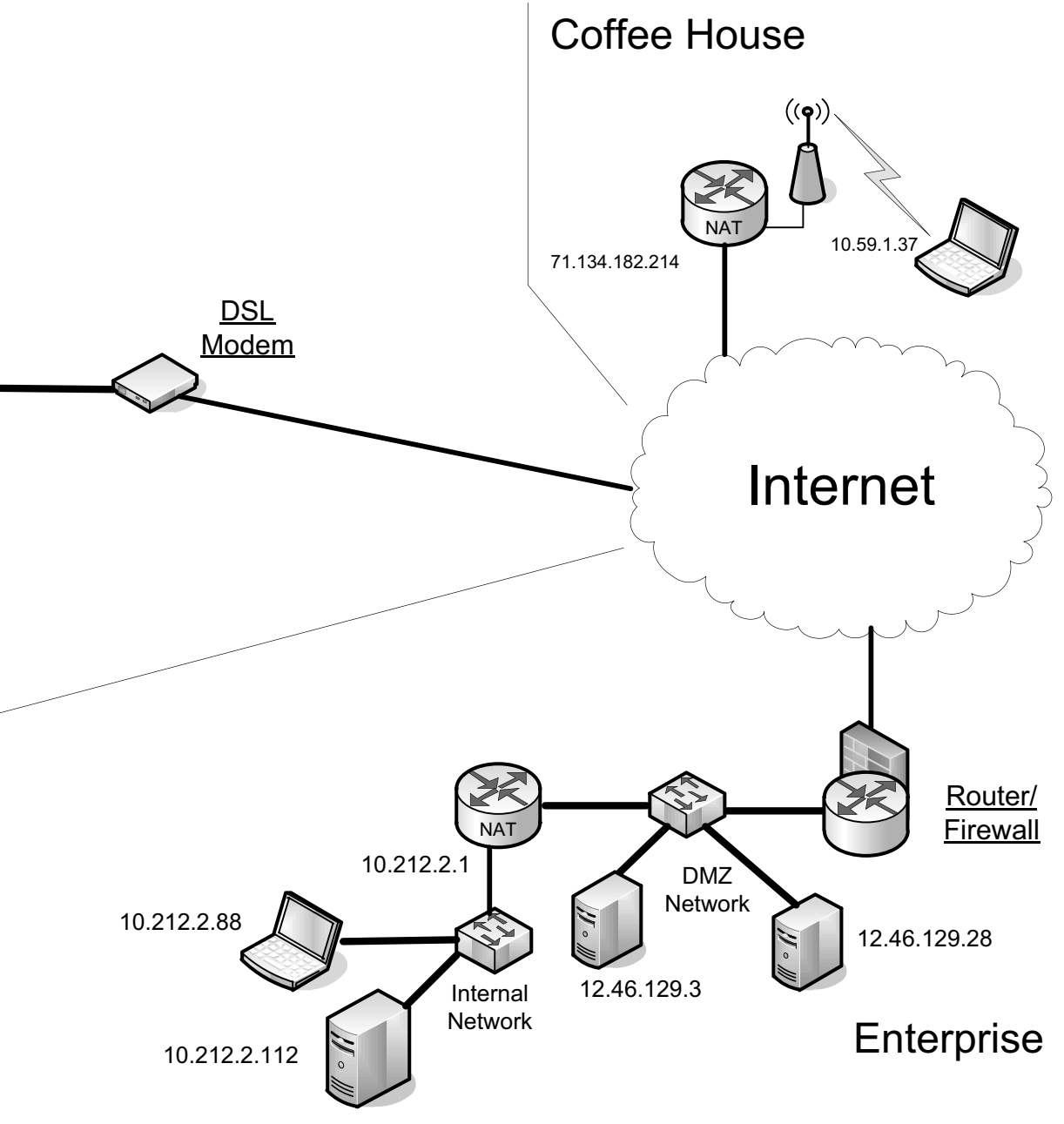

Public IP Addresses:
63.204.134.177
63.203.72.138
71.141.244.213
70.231.159.254
70.231.136.162
70.231.128.151
70.231.141.59
70.231.143.234
71.141.227.30
192.168.0.2
192.168.1.1
192.168.0.93
PPP / Ethernet
Test Connection
Wi-Fi
Access Point
192.168.0.1
10.0.0.1
Linux PC
(router, firewall, DHCP,
NAT, DNS)
Dynamic
IP Addresses
10.0.0.{15-126}
10.0.0.6
10.0.0.2
Dynamic
IP Addresses
10.0.1.{1-50}
switch
10.0.0.14
10.0.0.{7-13}
10.0.0.3
10.0.0.4
Home


Coffee House
NAT
71.134.182.214
10.59.1.37
DSL
Modem
Internet
NAT
10.212.2.1
Router/
Firewall
DMZ
Network
10.212.2.88
Internal
Network
12.46.129.3
12.46.129.28
10.212.2.112
Enterprise

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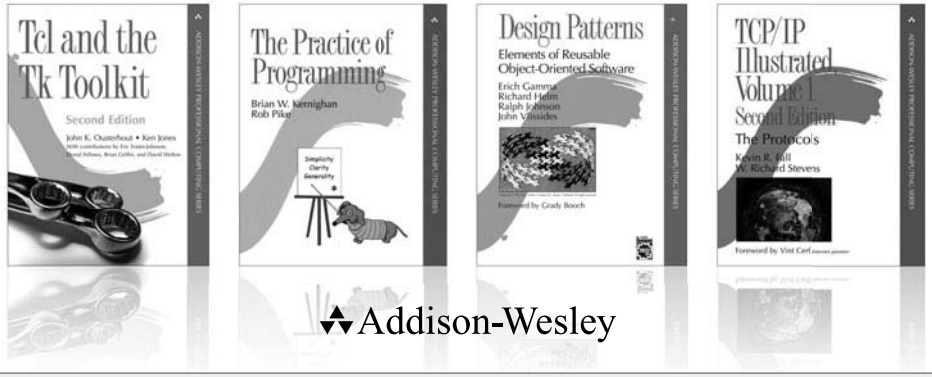

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The Protocols

Second Edition

Kevin R. Fall
W. Richard Stevens

Originally written by Dr. W. Richard Stevens.
Revised by Dr. Kevin R. Fall.

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To Vicki, George, Audrey, Maya, Dylan, and Jan,
for their insight, tolerance, and support
through the long nights and weekends.

—Kevin

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Foreword

Rarely does one find a book on a well-known topic that is both historically and technically comprehensive and remarkably accurate. One of the things I admire about this work is the "warts and all" approach that gives it such credibility. The TCP/IP architecture is a product of the time in which it was conceived. That it has been able to adapt to growing requirements in many dimensions by factors of a million or more, to say nothing of a plethora of applications, is quite remarkable. Understanding the scope and limitations of the architecture and its protocols is a sound basis from which to think about future evolution and even revolution.

During the early formulation of the Internet architecture, the notion of "enterprise" was not really recognized. In consequence, most networks had their own IP address space and "announced" their addresses in the routing system directly. After the introduction of commercial service, Internet Service Providers emerged as intermediaries who "announced" Internet address blocks on behalf of their customers. Thus, most of the address space was assigned in a "provider dependent" fashion. "Provider independent" addressing was unusual. The net result (no pun intended) led to route aggregation and containment of the size of the global routing table. While this tactic had benefits, it also created the "multi-homing" problem since users of provider-dependent addresses did not have their own entries in the global routing table. The IP address "crunch" also led to Network Address Translation, which also did not solve provider dependence and multi-homing problems.

Reading through this book evokes a sense of wonder at the complexity that has evolved from a set of relatively simple concepts that worked with a small number of networks and application circumstances. As the chapters unfold, one can see the level of complexity that has evolved to accommodate an increasing number of requirements, dictated in part by new deployment conditions and challenges, to say nothing of sheer growth in the scale of the system.

The issues associated with securing "enterprise" users of the Internet also led to firewalls that are intended to supply perimeter security. While useful, it has become clear that attacks against local Internet infrastructure can come through

internal compromises (e.g., an infected computer is put onto an internal network or an infected thumb-drive is used to infect an internal computer through its USB port).

It has become apparent that, in addition to a need to expand the Internet address space through the introduction of IP version 6, with its 340 trillion trillion trillion addresses, there is also a strong need to introduce various security-enhancing mechanisms such as the Domain Name System Security Extension (DNSSEC) among many others.

What makes this book unique, in my estimation, is the level of detail and attention to history. It provides background and a sense for the ways in which solutions to networking problems have evolved. It is relentless in its effort to achieve precision and to expose remaining problem areas. For an engineer determined to refine and secure Internet operation or to explore alternative solutions to persistent problems, the insights provided by this book will be invaluable. The authors deserve credit for a thorough rendering of the technology of today's Internet.

Woodhurst Vint Cerf
June 2011

Preface to the Second Edition

Welcome to the second edition of *TCP/IP Illustrated, Volume 1*. This book aims to provide a detailed, current look at the TCP/IP protocol suite. Instead of just describing how the protocols operate, we show the protocols in operation using a variety of analysis tools. This helps you better understand the design decisions behind the protocols and how they interact with each other, and it simultaneously exposes you to implementation details without your having to read through the implementation's software source code or set up an experimental laboratory. Of course, reading source code or setting up a laboratory will only help to increase your understanding.

Networking has changed dramatically in the past three decades. Originally a research project and object of curiosity, the Internet has become a global communication fabric upon which governments, businesses, and individuals depend. The TCP/IP suite defines the underlying methods used to exchange information by every device on the Internet. After more than a decade of delay, the Internet and TCP/IP itself are now undergoing an evolution, to incorporate IPv6. Throughout the text we will discuss both IPv6 and the current IPv4 together, but we highlight the differences where they are important. Unfortunately, they do not directly interoperate, so some care and attention are required to appreciate the impact of the evolution.

The book is intended for anyone wishing to better understand the current set of TCP/IP protocols and how they operate: network operators and administrators, network software developers, students, and users who deal with TCP/IP. We have included material that should be of interest to both new readers as well as those familiar with the material from the first edition. We hope you will find the coverage of the new and older material useful and interesting.

Comments on the First Edition

Nearly two decades have passed since the publication of the first edition of *TCP/IP Illustrated, Volume 1*. It continues to be a valuable resource for both students and professionals in understanding the TCP/IP protocols at a level of detail difficult to

obtain in competing texts. Today it remains among the best references for detailed information regarding the operation of the TCP/IP protocols. However, even the best books concerned with information and communications technology become dated after a time, and the TCP/IP Illustrated series is no exception. In this edition, I hope to thoroughly update the pioneering work of Dr. Stevens with coverage of new material while maintaining the exceptionally high standard of presentation and detail common to his numerous books.

The first edition covers a broad set of protocols and their operation, ranging from the link layer all the way to applications and network management. Today, covering this breadth of material comprehensively in a single volume would produce a very lengthy text indeed. For this reason, the second edition focuses specifically on the *core* protocols: those relatively low-level protocols used most frequently in providing the basic services of configuration, naming, data delivery, and security for the Internet. Detailed discussions of applications, routing, Web services, and other important topics are postponed to subsequent volumes.

Considerable progress has been made in improving the robustness and compliance of TCP/IP implementations to their corresponding specifications since the publication of the first edition. While many of the examples in the first edition highlight implementation bugs or noncompliant behaviors, these problems have largely been addressed in currently available systems, at least for IPv4. This fact is not terribly surprising, given the greatly expanded use of the TCP/IP protocols in the last 18 years. Misbehaving implementations are a comparative rarity, which attests to a certain maturity of the protocol suite as a whole. The problems encountered in the operation of the core protocols nowadays often relate to intentional exploitation of infrequently used protocol features, a form of security concern that was not a primary focus in the first edition but one that we spend considerable effort to address in the second edition.

The Internet Milieu of the Twenty-first Century

The usage patterns and importance of the Internet have changed considerably since the publication of the first edition. The most obvious watershed event was the creation and subsequent intense commercialization of the World Wide Web starting in the early 1990s. This event greatly accelerated the availability of the Internet to large numbers of people with various (sometimes conflicting) motivations. As such, the protocols and systems originally implemented in a small-scale environment of academic cooperation have been stressed by limited availability of addresses and an increase of security concerns.

In response to the security threats, network and security administrators have introduced special control elements into the network. It is now common practice to place a *firewall* at the point of attachment to the Internet, for both large enterprises as well as small businesses and homes. As the demand for IP addresses and security has increased over the last decade, *Network Address Translation* (NAT) is now supported in virtually all current-generation routers and is in widespread use. It

has eased the pressure on Internet address availability by allowing sites to obtain a comparatively small number of routable Internet addresses from their service providers (one for each simultaneously online user), yet assign a very large number of addresses to local computers without further coordination. A consequence of NAT deployment has been a slowing of the migration to IPv6 (which provides for an almost incomprehensibly large number of addresses) and interoperability problems with some older protocols.

As the users of personal computers began to demand Internet connectivity by the mid-1990s, the largest supplier of PC software, Microsoft, abandoned its original policy of offering only proprietary alternatives to the Internet and instead undertook an effort to embrace TCP/IP compatibility in most of its products. Since then, personal computers running their Windows operating system have come to dominate the mix of PCs presently connected to the Internet. Over time, a significant rise in the number of Linux-based systems means that such systems now threaten to displace Microsoft as the frontrunner. Other operating systems, including Oracle Solaris and Berkeley's BSD-based systems, which once represented the majority of Internet-connected systems, are now a comparatively small component of the mix. Apple's OS X (Mach-based) operating system has risen as a new contender and is gaining in popularity, especially among portable computer users. In 2003, portable computer (laptop) sales exceeded desktop sales as the majority of personal computer types sold, and their proliferation has sparked a demand for widely deployed, high-speed Internet access supported by wireless infrastructure. It is projected that the most common method for accessing the Internet from 2012 and beyond will be smartphones. Tablet computers also represent an important growing contender.

Wireless networks are now available at a large number of locations such as restaurants, airports, coffeehouses, and other public places. They typically provide short-range free or pay-for-use (flat-rate) high-speed wireless Internet connections using hardware compatible with commonly used office or home local area network installations. A set of alternative "wireless broadband" technologies based on cellular telephone standards (e.g., LTE, HSPA, UMTS, EV-DO) are becoming widely available in developed regions of the world (and some developing regions of the words that are "leapfrogging" to newer wireless technology), offering longer-range operation, often at somewhat reduced bandwidths and with volume-based pricing. Both types of infrastructure address the desire of users to be mobile while accessing the Internet, using either portable computers or smaller devices. In either case, mobile end users accessing the Internet over wireless networks pose two significant technical challenges to the TCP/IP protocol architecture. First, mobility affects the Internet's routing and addressing structure by breaking the assumption that hosts have addresses assigned to them based upon the identity of their nearby router. Second, wireless links may experience outages and therefore cause data to be lost for reasons other than those typical of wired links (which generally do not lose data unless too much traffic is being injected into the network).

Finally, the Internet has fostered the rise of so-called peer-to-peer applications forming "overlay" networks. Peer-to-peer applications do not rely on a central server to accomplish a task but instead determine a set of *peer* computers with which they can communicate and interact to accomplish a task. The peer computers are operated by other end users and may come and go rapidly compared to a fixed server infrastructure. The "overlay" concept captures the fact that such interacting peers themselves form a network, overlaid atop the conventional TCP/IP-based network (which, one may observe, is itself an overlay above the underlying physical links). The development of peer-to-peer applications, while of intense interest to those who study traffic flows and electronic commerce, has not had a profound impact on the core protocols described in *Volume 1* per se, but the concept of overlay networks has become an important consideration for networking technology more generally.

Content Changes for the Second Edition

Regarding content in the text, the most important changes from the first edition are a restructuring of the scope of the overall text and the addition of significant material on security. Instead of attempting to cover nearly all common protocols in use at every layer in the Internet, the present text focuses in detail first on the non-security core protocols in widespread use, or that are expected to be in widespread use in the near future: Ethernet (802.3), Wi-Fi (802.11), PPP, ARP, IPv4, IPv6, UDP, TCP, DHCP, and DNS. These protocols are likely to be encountered by system administrators and users alike.

In the second edition, security is covered in two ways. First, in each appropriate chapter, a section devoted to describing known attacks and their countermeasures relating to the protocol described in the chapter is included. These descriptions are not presented as a recipe for constructing attacks but rather as a practical indication of the kinds of problems that may arise when protocol implementations (or specifications, in some cases) are insufficiently robust. In today's Internet, incomplete specification or lax implementation practice can lead to mission-critical systems being compromised by even relatively unsophisticated attacks.

The second important discussion of security occurs in Chapter 18, where security and cryptography are studied in some detail, including protocols such as IPsec, TLS, DNSSEC, and DKIM. These protocols are now understood to be important for implementing any service or application expected to maintain integrity or secure operation. As the Internet has increased in commercial importance, the need for security (and the number of threats to it) has grown proportionally.

Although IPv6 was not included in the first edition, there is now reason to believe that the use of IPv6 may increase significantly with the exhaustion of unallocated IPv4 address groups in February 2011. IPv6 was conceived largely to address the problems of IPv4 address depletion and, and while not nearly as common as IPv4 today, is becoming more important as a growing number of small devices (such as cellular telephones, household devices, and environmental

sensors) become attached to the Internet. Events such as the World IPv6 Day (June 8, 2011) helped to demonstrate that the Internet can continue to work even as the underlying protocols are modified and augmented in a significant way.

A second consideration for the structure of the second edition is a deemphasis of the protocols that are no longer commonly used and an update of the descriptions of those that have been revised substantially since the publication of the first edition. The chapters covering RARP, BOOTP, NFS, SMTP, and SNMP have been removed from the book, and the discussion of the SLIP protocol has been abandoned in favor of expanded coverage of DHCP and PPP (including PPPoE). The function of IP forwarding (described in Chapter 9 in the first edition) has been integrated with the overall description of the IPv4 and IPv6 protocols in Chapter 5 of this edition. The discussion of dynamic routing protocols (RIP, OSPF, and BGP) has been removed, as the latter two protocols alone could each conceivably merit a book-long discussion. Starting with ICMP, and continuing through IP, TCP, and UDP, the impact of operation using IPv4 versus IPv6 is discussed in any cases where the difference in operation is significant. There is no specific chapter devoted solely to IPv6; instead, its impact relative to each existing core protocol is described where appropriate. Chapters 15 and 25–30 of the first edition, which are devoted to Internet applications and their supporting protocols, have been largely removed; what remains only illustrates the operation of the underlying core protocols where necessary.

Several chapters covering new material have been added. The first chapter begins with a general introduction to networking issues and architecture, followed by a more Internet-specific orientation. The Internet's addressing architecture is covered in Chapter 2. A new chapter on host configuration and how a system "gets on" the network appears as Chapter 6. Chapter 7 describes firewalls and Network Address Translation (NAT), including how NATs are used in partitioning address space between routable and nonroutable portions. The set of tools used in the first edition has been expanded to include Wireshark (a free network traffic monitor application with a graphical user interface).

The target readership for the second edition remains identical to that of the first edition. No prior knowledge of networking concepts is required for approaching it, although the advanced reader should benefit from the level of detail and references. A rich collection of references is included in each chapter for the interested reader to pursue.

Editorial Changes for the Second Edition

The general flow of material in the second edition remains similar to that of the first edition. After the introductory material (Chapters 1 and 2), the protocols are presented in a bottom-up fashion to illustrate how the goal of network communication presented in the introduction is realized in the Internet architecture. As in the first edition, actual packet traces are used to illustrate the operational details of the protocols, where appropriate. Since the publication of the first edition, freely

available packet capture and analysis tools with graphical interfaces have become available, extending the capabilities of the `tcpdump` program used in the first edition. In the present text, `tcpdump` is used when the points to be illustrated are easily conveyed by examining the output of a text-based packet capture tool. In most other cases, however, screen shots of the Wireshark tool are used. Please be aware that some output listings, including snapshots of `tcpdump` output, are wrapped or simplified for clarity.

The packet traces shown typically illustrate the behavior of one or more parts of the network depicted on the inside of the front book cover. It represents a broadband-connected "home" environment (typically used for client access or peer-to-peer networking), a "public" environment (e.g., coffee shop), and an enterprise environment. The operating systems used for examples include Linux, Windows, FreeBSD, and Mac OS X. Various versions are used, as many different OS versions are in use on the Internet today.

The structure of each chapter has been slightly modified from the first edition. Each chapter begins with an introduction to the chapter topic, followed in some cases by historical notes, the details of the chapter, a summary, and a set of references. A section near the end of most chapters describes security concerns and attacks. The per-chapter references represent a change for the second edition. They should make each chapter more self-contained and require the reader to perform fewer "long-distance page jumps" to find a reference. Some of the references are now enhanced with WWW URLs for easier access online. In addition, the reference format for papers and books has been changed to a somewhat more compact form that includes the first initial of each author's last name followed by the last two digits of the year (e.g., the former [Cerf and Kahn 1974] is now shortened to [CK74]). For the numerous RFC references used, the RFC number is used instead of the author names. This follows typical RFC conventions and has the side benefit of grouping all the RFC references together in the reference lists.

On a final note, the typographical conventions of the TCP/IP Illustrated series have been maintained faithfully. However, the present author elected to use an editor and typesetting package other than the Troff system used by Dr. Stevens and some other authors of the Addison-Wesley Professional Computing Series collection. Thus, the particular task of final copyediting could take advantage of the significant expertise of Barbara Wood, the copy editor generously made available to me by the publisher. We hope you will be pleased with the results.

Berkeley, California Kevin R. Fall
September 2011

Adapted Preface to the First Edition

Introduction

This book describes the TCP/IP protocol suite, but from a different perspective than other texts on TCP/IP. Instead of just describing the protocols and what they do, we'll use a popular diagnostic tool to watch the protocols in action. Seeing how the protocols operate in varying circumstances provides a greater understanding of how they work and why certain design decisions were made. It also provides a look into the implementation of the protocols, without having to wade through thousands of lines of source code.

When networking protocols were being developed in the 1960s through the 1980s, expensive, dedicated hardware was required to see the packets going "across the wire." Extreme familiarity with the protocols was also required to comprehend the packets displayed by the hardware. Functionality of the hardware analyzers was limited to that built in by the hardware designers.

Today this has changed dramatically with the ability of the ubiquitous workstation to monitor a local area network [Mogul 1990]. Just attach a workstation to your network, run some publicly available software, and watch what goes by on the wire. While many people consider this a tool to be used for *diagnosing* network problems, it is also a powerful tool for *understanding* how the network protocols operate, which is the goal of this book.

This book is intended for anyone wishing to understand how the TCP/IP protocols operate: programmers writing network applications, system administrators responsible for maintaining computer systems and networks utilizing TCP/IP, and users who deal with TCP/IP applications on a daily basis.

Typographical Conventions

When we display interactive input and output we'll show our typed input in a **bold font**, and the computer output like this. *Comments are added in italics.*

```
bsdi % telnet svr4 discard          connect to the discard server
Trying 140.252.13.34...             this line and next output by Telnet client
Connected to svr4.
```

Also, we always include the name of the system as part of the shell prompt (bsdi in this example) to show on which host the command was run.

Note

Throughout the text we'll use indented, parenthetical notes such as this to describe historical points or implementation details.

We sometimes refer to the complete description of a command on the Unix manual as in ifconfig(8). This notation, the name of the command followed by a number in parentheses, is the normal way of referring to Unix commands. The number in parentheses is the section number in the Unix manual of the "manual page" for the command, where additional information can be located. Unfortunately not all Unix systems organize their manuals the same, with regard to the section numbers used for various groupings of commands. We'll use the BSD-style section numbers (which is the same for BSD-derived systems such as SunOS 4.1.3), but your manuals may be organized differently.

Acknowledgments

Although the author's name is the only one to appear on the cover, the combined effort of many people is required to produce a quality text book. First and foremost is the author's family, who put up with the long and weird hours that go into writing a book. Thank you once again, Sally, Bill, Ellen, and David.

The consulting editor, Brian Kernighan, is undoubtedly the best in the business. He was the first one to read various drafts of the manuscript and mark it up with his infinite supply of red pens. His attention to detail, his continual prodding for readable prose, and his thorough reviews of the manuscript are an immense resource to a writer.

Technical reviewers provide a different point of view and keep the author honest by catching technical mistakes. Their comments, suggestions, and (most importantly) criticisms add greatly to the final product. My thanks to Steve Bellovin, Jon Crowcroft, Pete Haverlock, and Doug Schmidt for comments on the entire manuscript. Equally valuable comments were provided on portions of the manuscript by Dave Borman for his thorough review of all the TCP chapters, and to Bob Gilligan who should be listed as a coauthor for Appendix E.

An author cannot work in isolation, so I would like to thank the following persons for lots of small favors, especially by answering my numerous e-mail questions: Joe Godsil, Jim Hogue, Mike Karels, Paul Lucchina, Craig Partridge, Thomas Skibo, and Jerry Toporek.

This book is the result of my being asked lots of questions on TCP/IP for which I could find no quick, immediate answer. It was then that I realized that the easiest way to obtain the answers was to run small tests, forcing certain conditions to occur, and just watch what happens. I thank Peter Haverlock for asking the probing questions and Van Jacobson for providing so much of the publicly available software that is used in this book to answer the questions.

A book on networking needs a real network to work with along with access to the Internet. My thanks to the National Optical Astronomy Observatories (NOAO), especially Sidney Wolff, Richard Wolff, and Steve Grandi, for providing access to their networks and hosts. A special thanks to Steve Grandi for answering lots of questions and providing accounts on various hosts. My thanks also to Keith Bostic and Kirk McKusick at the U.C. Berkeley CSRG for access to the latest 4.4BSD system.

Finally, it is the publisher that pulls everything together and does whatever is required to deliver the final product to the readers. This all revolves around the editor, and John Wait is simply the best there is. Working with John and the rest of the professionals at Addison-Wesley is a pleasure. Their professionalism and attention to detail show in the end result.

Camera-ready copy of the book was produced by the author, a Troff die-hard, using the Groff package written by James Clark.

Tucson, Arizona W. Richard Stevens
October 1993

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12

TCP: The Transmission Control Protocol (Preliminaries)

12.1 Introduction

So far we have been discussing protocols that do not include their own mechanisms for delivering data reliably. They may *detect* that erroneous data has been received, using a mathematical function such as a checksum or CRC, but they do not try very hard to repair errors. With IP and UDP, no error repair is done at all. With Ethernet and other protocols based on it, the protocol provides some number of retries and then gives up if it cannot succeed.

The problem of communicating in environments where the communication medium may lose or alter the messages being delivered has been studied for years. Some of the most important theoretical work on the topic was developed by Claude Shannon in 1948 [S48]. This work, which popularized the term bit and became the foundation of the field of *information theory*, helps us understand the fundamental limits on the amount of information that can be moved across an information channel that is *lossy* (that may delete or alter bits). Information theory is closely related to the field of *coding theory*, which provides ways of encoding information so that it is as resilient as possible to errors in the communications channel. Using *error-correcting codes* (basically, adding redundant bits so that the real information can be retrieved even if some bits are damaged) to correct communications problems is one very important method for handling errors. Another is to simply "try sending again" until the information is finally received. This approach, called *Automatic Repeat Request* (ARQ), forms the basis for many communications protocols, including TCP.

12.1.1 ARQ and Retransmission

If we consider not only a single communication channel but the multihop cascade of several, we realize that not only may we have the types of errors mentioned so far (packet bit errors), but there may be others. These problems might arise at an intermediate router and are the types of problems we brought up when discussing IP: packet reordering, packet duplication, and packet erasures (drops). An error-correcting protocol designed for use over a multihop communications channel (such as IP) must cope with all of these problems. Let us now explore the protocol mechanisms that can be brought to bear on them. After we discuss these in the abstract, we shall explore how they are used by TCP in the Internet.

A straightforward method of dealing with packet drops (and bit errors) is to resend the packet until it is received properly. This requires a way to determine (1) whether the receiver has received the packet and (2) whether the packet it received was the same one the sender sent. The method for a receiver to signal to a sender that it has received a packet is called an *acknowledgment*, or ACK. In its most basic form, the sender sends a packet and awaits an ACK. When the receiver receives the packet, it sends the ACK. When the sender receives the ACK, it sends another packet, and the process continues. Interesting questions to ask here are (1) How long should the sender wait for an ACK? (2) What if the ACK is lost? (3) What if the packet was received but had errors in it?

As we shall see, the first question turns out to be deep. Deciding how long to wait relates to how long the sender should *expect* to wait for an ACK. Determining this may be difficult; we postpone the discussion of techniques for it until we discuss TCP in detail later (see Chapter 14). The answer to question 2 is easier: if an ACK is dropped, the sender cannot readily distinguish this case from the case in which the original packet is dropped, so it simply sends the packet again. Of course, the receiver may receive two or more copies in that case, so it must be prepared to handle that situation (see the next paragraph). As for the third question, we can appeal to the codes mentioned in Section 12.1. It is generally much easier to use codes to *detect* errors in a large packet (with high probability) using only a few bits than it is to correct them. Simpler codes are typically not capable of correcting errors but are capable of detecting them. That is why checksums and CRCs are so popular. In order to detect errors in a packet, then, we use a form of checksum. When a receiver receives a packet containing an error, it refrains from sending an ACK. Eventually, the sender resends the packet, which ideally arrives undamaged.

Even with the simple scenario presented so far, there is the possibility that the receiver might receive *duplicate* copies of the packet being transferred. This problem is addressed using a *sequence number*. Basically, every unique packet gets a new sequence number when it is sent at the source, and this sequence number is carried along in the packet itself. The receiver can use this number to determine whether it has already seen the packet and if so, discard it.

The protocol described so far is reliable but not very efficient. Consider what happens when the time to deliver even a small packet from sender to receiver (the

delay or latency) is large (e.g., a second or two, which is not unusual for satellite links) and there are several packets to send. The sender is able to inject a single packet into the communications path but then must stop until it hears the ACK. This protocol is therefore called "stop and wait." Its throughput performance (data sent on the network per unit time) is proportional to M/R where M is the packet size and R is the round-trip time (RTT), assuming no packets are lost or irreparably damaged in transit. For a fixed-size packet, as R goes up, the throughput goes down. If packets are lost or damaged, the situation is even worse: the "goodput" (useful amount of data transferred per unit time) can be considerably less than the throughput.

For a network that doesn't damage or drop many packets, the cause for low throughput is usually that the network is not being kept busy. The situation is similar to using an assembly line where new work cannot enter the line until a complete product emerges. Most of the line goes idle. If we take this comparison one step further, it seems obvious that we would do better if we could have more than one work unit in the line at a time. It is the same for network communication—if we could have more than one packet in the network, we would keep it "more busy," leading to higher throughput.

Allowing more than one packet to be in the network at a time complicates matters considerably. Now the sender must decide not only when to inject a packet into the network, but also how many. It also must figure out how to keep the timers when waiting for ACKs, and it must keep a copy of each packet not yet acknowledged in case retransmissions are necessary. The receiver needs to have a more sophisticated ACK mechanism: one that can distinguish which packets have been received and which have not. The receiver may need a more sophisticated buffering (packet storage) mechanism—one that allows it to hold "out-of-sequence" packets (those packets that have arrived earlier than those expected because of loss or reordering), unless it simply wants to throw away such packets, which is very inefficient. There are other issues that may not be so obvious. What if the receiver is slower than the sender? If the sender simply injects many packets at a very high rate, the receiver might just drop them because of processing or memory limitations. The same question can be asked about the routers in the middle. What if the network infrastructure cannot handle the rate of data the sender and receiver wish to use?

12.1.2 Windows of Packets and Sliding Windows

To handle all of these problems, we begin with the assumption that each unique packet has a sequence number, as described earlier. We define a *window* of packets as the collection of packets (or their sequence numbers) that have been injected by the sender but not yet completely acknowledged (i.e., the sender has not received an ACK for them). We refer to the *window size* as the number of packets in the window. The term *window* comes from the idea that if you lined up all the packets sent during a communication session in a long row but had only a small aperture

through which to view them, you would see only a subset of them—like peering through a window. The sender's window (and the line of other packets) can be graphically depicted as shown in Figure 12-1.

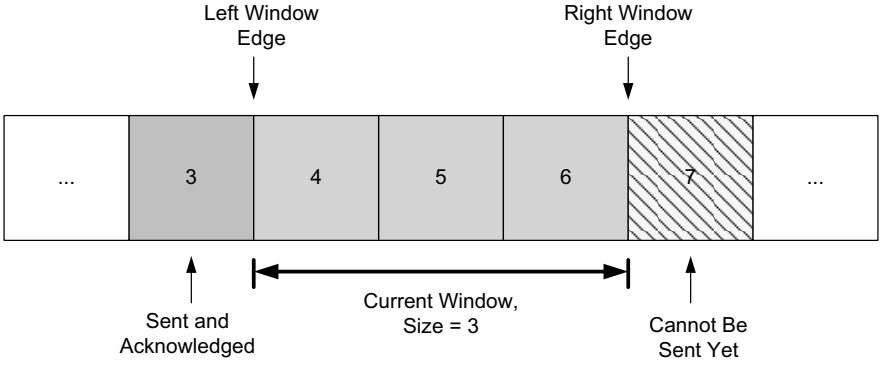

Figure 12-1 The sender's window, showing which packets are eligible to be sent (or have already been sent), which are not yet eligible, and which have already been sent and acknowledged. In this example, the window size is fixed at three packets.

This figure shows the current window of three packets, for a total window size of 3. Packet number 3 has already been sent and acknowledged, so the copy of it that the sender was keeping can now be released. Packet 7 is ready at the sender but not yet able to be sent because it is not yet "in" the window. If we now imagine that data starts to flow from the sender to the receiver and ACKs start to flow in the reverse direction, the sender might next receive an ACK for packet 4. When this happens, the window "slides" to the right by one packet, meaning that the copy of packet 4 can be released and packet 7 can be sent. This movement of the window gives rise to another name for this type of protocol, a *sliding window* protocol.

The sliding window approach can be used to combat many of the problems described so far. Typically, this window structure is kept at both the sender and the receiver. At the sender, it keeps track of what packets can be released, what packets are awaiting ACKs, and what packets cannot yet be sent. At the receiver, it keeps track of what packets have already been received and acknowledged, what packets are expected (and how much memory has been allocated to hold them), and which packets, even if received, will not be kept because of limited memory. Although the window structure is convenient for keeping track of data as it flows between sender and receiver, it does not provide guidance as to how large the window should be, or what happens if the receiver or network cannot handle the sender's data rate. We shall now see how these are related.

12.1.3 Variable Windows: Flow Control and Congestion Control

To handle the problem that arises when a receiver is too slow relative to a sender, we introduce a way to force the sender to slow down when the receiver cannot keep up. This is called *flow control* and is usually handled in one of two ways. One way, called *rate-based* flow control, gives the sender a certain data rate allocation and ensures that data is never allowed to be sent at a rate that exceeds the allocation. This type of flow control is most appropriate for streaming applications and can be used with broadcast and multicast delivery (see Chapter 9).

The other predominant form of flow control is called *window-based* flow control and is the most popular approach when sliding windows are being used. In this approach, the window size is not fixed but is instead allowed to vary over time. To achieve flow control using this technique, there must be a method for the receiver to signal the sender how large a window to use. This is typically called a *window advertisement*, or simply a *window update*. This value is used by the sender (i.e., the receiver of the window advertisement) to adjust its window size. Logically, a window update is separate from the ACKs we discussed previously, but in practice the window update and ACK are carried in a single packet, meaning that the sender tends to adjust the size of its window at the same time it slides it to the right.

If we consider the effect of changing the window size at the sender, it becomes clear how this achieves flow control. The sender is allowed to inject W packets into the network before it hears an ACK for any of them. If the sender and receiver are sufficiently fast, and the network loses no packets and has an infinite capacity, this means that the transfer rate is proportional to (SW/R) bits/s, where W is the window size, S is the packet size in bits, and R is the RTT. When the window advertisement from the receiver clamps the value of W at the sender, the sender's overall rate can be limited so as to not overwhelm the receiver. This approach works fine for protecting the receiver, but what about the network in between? We may have routers with limited memory between the sender and the receiver that have to contend with slow network links. When this happens, it is possible for the sender's rate to exceed a router's ability to keep up, leading to packet loss. This is addressed with a special form of flow control called *congestion control*.

Congestion control involves the sender slowing down so as to not overwhelm the network between itself and the receiver. Recall that in our discussion of flow control, we used a window advertisement to signal the sender to slow down for the receiver. This is called *explicit* signaling, because there is a protocol field specifically used to inform the sender about what is happening. Another option might be for the sender to *guess* that it needs to slow down. Such an approach would involve *implicit* signaling—that is, it would involve deciding to slow down based on some other evidence.

The problem of congestion control in datagram-style networks, and more generally *queuing theory* to which it is closely related, has remained a major research topic for years, and it is unlikely to ever be solved completely for all circumstances. It is also not practical to discuss all the options and methods of performing flow

control here. The interested reader is referred to [J90], [K97], and [K75]. In Chapter 16 we will explore the particular congestion control technique used with TCP in more detail, along with a number of variants that have arisen over the years.

12.1.4 Setting the Retransmission Timeout

One of the most important performance issues the designer of a retransmission-based reliable protocol faces is how long to wait before concluding that a packet has been lost and should be resent. Stated another way, What should the retransmission timeout be? Intuitively, the amount of time the sender should wait before resending a packet is about the sum of the following times: the time to send the packet, the time for the receiver to process it and send an ACK, the time for the ACK to travel back to the sender, and the time for the sender to process the ACK. Unfortunately, in practice, none of these times are known with certainty. To make matters worse, any or all of them vary over time as additional load is added to or removed from the end hosts or routers.

Because it is not practical for the user to tell the protocol implementation what the values of all the times are (or to keep them up-to-date) for all circumstances, a better strategy is to have the protocol implementation try to estimate them. This is called *round-trip-time estimation* and is a statistical process. Basically, the true RTT is likely to be close to the sample mean of a collection of samples of RTTs. Note that this average naturally changes over time (it is not stationary), as the paths taken through the network may change.

Once some estimate of the RTT is made, the question of setting the actual timeout value, used to trigger retransmissions, remains. If we recall the definition of a mean, it can never be the extreme value of a set of samples (unless they are all the same). So, it would not be sensible to set the retransmission timer to be exactly equal to the mean estimator, as it is likely that many actual RTTs will be larger, thereby inducing unwanted retransmissions. Clearly, the timeout should be set to something larger than the mean, but exactly what this relationship is (or even if the mean should be directly used) is not yet clear. Setting the timeout too large is also undesirable, as this leads back to letting the network go idle, reducing throughput. We shall defer further exploration of this topic to Chapter 14, where we explore how TCP, in particular, approaches this problem.

12.2 Introduction to TCP

Given the background we now have regarding the issues affecting reliable delivery in general, let us see how they play out in TCP and what type of service it provides to Internet applications. We also look at the fields in the TCP header, noticing how many of the concepts we have seen so far (e.g., ACKs, window advertisements) are captured in the header description. In the chapters that follow, we examine all of these header fields in more detail.

Our description of TCP starts in this chapter and continues in the next five chapters. Chapter 13 describes how a TCP connection is established and terminated. Chapter 14 details how TCP estimates the per-connection RTT and how the retransmission timeout is set based on this estimate. Chapter 15 looks at the normal transfer of data, starting with "interactive" applications (such as chat). It then covers window management and flow control, which apply to both interactive and "bulk" data flow applications (such as file transfer), along with TCP's *urgent mechanism*, which allows a sender to mark certain data in the data stream as special. Chapter 16 takes a look at congestion control algorithms in TCP that help to reduce packet loss when the network is very busy. It also discusses some modifications that have been proposed to increase throughput on fast networks or improve resiliency on lossy (e.g., wireless) networks. Finally, Chapter 17 shows how TCP keeps connections active even when no data is flowing.

The original specification for TCP is [RFC0793], although some errors in that RFC are corrected in the Host Requirements RFC, [RFC1122]. Since then, specifications for TCP have been revised and extended to include clarified and improved congestion control behavior [RFC5681][RFC3782][RFC3517][RFC3390][RFC3168], retransmission timeouts [RFC6298][RFC5682][RFC4015], operation with NATs [RFC5382], acknowledgment behavior [RFC2883], security [RFC6056][RFC5927][RFC5926], connection management [RFC5482], and urgent mechanism implementation guidelines [RFC6093]. There have also been a rich variety of experimental modifications covering retransmission behaviors [RFC5827][RFC3708], congestion detection and control [RFC5690][RFC5562][RFC4782][RFC3649][RFC2861], and other features. Finally, there is an effort to explore how TCP might take advantage of multiple simultaneous network-layer paths [RFC6182].

12.2.1 The TCP Service Model

Even though TCP and UDP use the same network layer (IPv4 or IPv6), TCP provides a totally different service to the application layer from what UDP does. TCP provides a *connection-oriented*, reliable, byte stream service. The term *connection-oriented* means that the two applications using TCP must establish a TCP connection by contacting each other before they can exchange data. The typical analogy is dialing a telephone number, waiting for the other party to answer the phone and saying "Hello," and then saying "Who's calling?" There are exactly two endpoints communicating with each other on a TCP connection; concepts such as broadcasting and multicasting (see Chapter 9) are not applicable to TCP.

TCP provides a byte stream abstraction to applications that use it. The consequence of this design decision is that no record markers or message boundaries are automatically inserted by TCP (see Chapter 1). A record marker corresponds to an indication of an application's write extent. If the application on one end writes 10 bytes, followed by a write of 20 bytes, followed by a write of 50 bytes, the application at the other end of the connection cannot tell what size the individual writes were. For example, the other end may read the 80 bytes in four reads of 20 bytes at a time or in some other way. One end puts a stream of bytes into TCP, and

the identical stream of bytes appears at the other end. Each endpoint individually chooses its read and write sizes.

TCP does not interpret the contents of the bytes in the byte stream at all. It has no idea if the data bytes being exchanged are binary data, ASCII characters, EBCDIC characters, or something else. The interpretation of this byte stream is up to the applications on each end of the connection. TCP does, however, support the urgent mechanism mentioned before, although it is no longer recommended for use.

12.2.2 Reliability in TCP

TCP provides reliability using specific variations on the techniques just described. Because it provides a byte stream interface, TCP must convert a sending application's stream of bytes into a set of packets that IP can carry. This is called *packetization*. These packets contain sequence numbers, which in TCP actually represent the byte offsets of the first byte in each packet in the overall data stream rather than packet numbers. This allows packets to be of variable size during a transfer and may also allow them to be combined, called *repacketization*. The application data is broken into what TCP considers the best-size chunks to send, typically fitting each segment into a single IP-layer datagram that will not be fragmented. This is different from UDP, where each write by the application usually generates a UDP datagram of that size (plus headers). The chunk passed by TCP to IP is called a *segment* (see Figure 12-2). In Chapter 15 we shall see how TCP decides what size a segment should be.

TCP maintains a mandatory checksum on its header, any associated application data, and fields from the IP header. This is an end-to-end pseudo-header checksum whose purpose is to detect any bit errors introduced in transit. If a segment arrives with an invalid checksum, TCP discards it without sending any acknowledgment for the discarded packet. The receiving TCP might acknowledge a *previous* (already acknowledged) segment, however, to help the sender with its congestion control computations (see Chapter 16). The TCP checksum uses the same mathematical function as is used by other Internet protocols (UDP, ICMP, etc.). For large data transfers, there is some concern that this checksum is not really strong enough [SP00], so careful applications should apply their own error protection methods (e.g., stronger checksums or CRCs) or use a middleware layer to achieve the same result (e.g., see [RFC5044]).

When TCP sends a group of segments, it normally sets a single retransmission timer, waiting for the other end to acknowledge reception. TCP does not set a different retransmission timer for every segment. Rather, it sets a timer when it sends a window of data and updates the timeout as ACKs arrive. If an acknowledgment is not received in time, a segment is retransmitted. In Chapter 14 we will look at TCP's adaptive timeout and retransmission strategy in more detail.

When TCP receives data from the other end of the connection, it sends an acknowledgment. This acknowledgment may not be sent immediately but is normally delayed a fraction of a second. The ACKs used by TCP are *cumulative* in the sense that an ACK indicating byte number N implies that all bytes up to number N

(but not including it) have already been received successfully. This provides some robustness against ACK loss—if an ACK is lost, it is very likely that a subsequent ACK is sufficient to ACK the previous segments.

TCP provides a *full-duplex* service to the application layer. This means that data can be flowing in each direction, independent of the other direction. Therefore, each end of a connection must maintain a sequence number of the data flowing in each direction. Once a connection is established, every TCP segment that contains data flowing in one direction of the connection also includes an ACK for segments flowing in the opposite direction. Each segment also contains a window advertisement for implementing flow control in the opposite direction. Thus, when a TCP segment arrives on a connection, the window may slide forward, the window size may change, and new data may have arrived. As we shall see in Chapter 13, a fully active TCP connection is bidirectional and symmetric; data can flow equally well in either direction.

Using sequence numbers, a receiving TCP discards duplicate segments and reorders segments that arrive out of order. Recall that any of these anomalies can happen because TCP uses IP to deliver its segments, and IP does not provide duplicate elimination or guarantee correct ordering. Because it is a byte stream protocol, however, TCP never delivers data to the receiving *application* out of order. Thus, the receiving TCP may be forced to hold on to data with larger sequence numbers before giving it to an application until a missing lower-sequence-numbered segment (a "hole") is filled in.

We will now begin to look at some of the details of TCP. In this chapter we will only introduce the encapsulation and header structure for TCP. Other details appear in the next five chapters. TCP can be used with IPv4 or IPv6, and the pseudo-header checksum it uses (similar to UDP's) is mandatory for use with either IPv4 or IPv6.

12.3 TCP Header and Encapsulation

TCP is encapsulated in IP datagrams as shown in Figure 12-2.

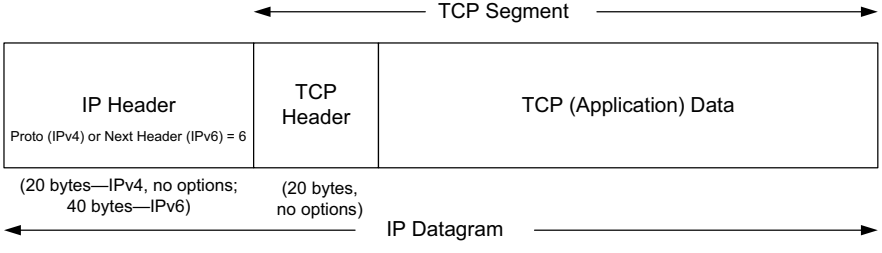

Figure 12-2 The TCP header appears immediately following the IP header or last IPv6 extension header and is often 20 bytes long (with no TCP options). With options, the TCP header can be as large as 60 bytes. Common options include Maximum Segment Size, Timestamps, Window Scaling, and Selective ACKs.

The header itself is considerably more complicated than the header we saw for UDP in Chapter 10. This is not very surprising, as TCP is a significantly more complicated protocol that must keep each end of the connection informed (synchronized) about the current state. It is shown in Figure 12-3.

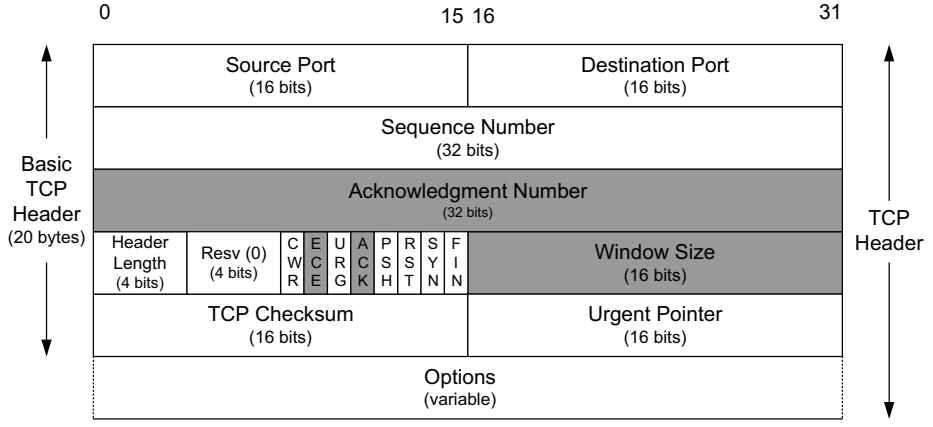

Figure 12-3 The TCP header. Its normal size is 20 bytes, unless options are present. The *Header Length* field gives the size of the header in 32-bit words (minimum value is 5). The shaded fields (*Acknowledgment Number*, *Window Size*, plus *ECE* and *ACK* bits) refer to the data flowing in the opposite direction relative to the sender of this segment.

Each TCP header contains the source and destination port number. These two values, along with the source and destination IP addresses in the IP header, uniquely identify each connection. The combination of an IP address and a port number is sometimes called an *endpoint* or *socket* in the TCP literature. The latter term appeared in [RFC0793] and was ultimately adopted as the name of the Berkeley-derived programming interface for network communications (now frequently called "Berkeley sockets"). It is a *pair* of sockets or endpoints (the 4-tuple consisting of the client IP address, client port number, server IP address, and server port number) that uniquely identifies each TCP connection. This fact will become important when we look at how a TCP server can communicate with multiple clients (see Chapter 13).

The *Sequence Number* field identifies the byte in the stream of data from the sending TCP to the receiving TCP that the first byte of data in the containing segment represents. If we consider the stream of bytes flowing in one direction between two applications, TCP numbers each *byte* with a sequence number. This sequence number is a 32-bit unsigned number that wraps back around to 0 after reaching $(2^{32}) - 1$. Because every byte exchanged is numbered, the *Acknowledgment Number* field (also called the *ACK Number* or *ACK* field for short) contains the next sequence number that the sender of the acknowledgment expects to receive. This is therefore the sequence number of the last successfully received byte of data plus 1. This field is valid only if the *ACK* bit field (described later in this section) is on,

which it usually is for all but initial and closing segments. Sending an ACK costs nothing more than sending any other TCP segment because the 32-bit *ACK Number* field is *always* part of the header, as is the *ACK* bit field.

When a new connection is being established, the *SYN* bit field is turned on in the first segment sent from client to server. Such segments are called *SYN segments*, or simply *SYNs*. The *Sequence Number* field then contains the first sequence number to be used on that direction of the connection for subsequent sequence numbers and in returning ACK numbers (recall that connections are all bidirectional). Note that this number is *not* 0 or 1 but instead is another number, often randomly chosen, called the *initial sequence number* (ISN). The reason for the ISN not being 0 or 1 is a security measure and will be discussed in Chapter 13. The sequence number of the first byte of data sent on this direction of the connection is the ISN plus 1 because the *SYN* bit field *consumes* one sequence number. As we shall see later, consuming a sequence number also implies reliable delivery using retransmission. Thus, SYNs and application bytes (and FINs, which we will see later) are reliably delivered. ACKs, which do not consume sequence numbers, are not.

TCP can be described as "a sliding window protocol with cumulative positive acknowledgments." The *ACK Number* field is constructed to indicate the largest byte received in order at the receiver (plus 1). For example, if bytes 1–1024 are received OK, and the next segment contains bytes 2049–3072, the receiver cannot use the regular *ACK Number* field to signal the sender that it received this new segment. Modern TCPs, however, have a *selective acknowledgment* (SACK) option that allows the receiver to indicate to the sender out-of-order data it has received correctly. When paired with a TCP sender capable of *selective repeat*, a significant performance benefit may be realized [FF96]. In Chapter 14 we will see how TCP uses *duplicate acknowledgments* (multiple segments with the same *ACK* field) to help with its congestion control and error control procedures.

The *Header Length* field gives the length of the header in 32-bit words. This is required because the length of the *Options* field is variable. With a 4-bit field, TCP is limited to a 60-byte header. Without options, however, the size is 20 bytes.

Currently eight bit fields are defined for the TCP header, although some older implementations understand only the last six of them.[1] One or more of them can be turned on at the same time. We briefly mention their use here and discuss each of them in more detail in later chapters.

1. ***CWR***—Congestion Window Reduced (the sender reduced its sending rate); see Chapter 16.
2. ***ECE***—ECN Echo (the sender received an earlier congestion notification); see Chapter 16.
3. ***URG***—Urgent (the *Urgent Pointer* field is valid—rarely used); see Chapter 15.

1. Note that [RFC3540], an experimental RFC, also defines the least significant of the Resv bits as a nonce sum (NS). See Section 16.12.

4. ***ACK***—Acknowledgment (the *Acknowledgment Number* field is valid—always on after a connection is established); see Chapters 13 and 15.
5. ***PSH***—Push (the receiver should pass this data to the application as soon as possible—not reliably implemented or used); see Chapter 15.
6. ***RST***—Reset the connection (connection abort, usually because of an error); see Chapter 13.
7. ***SYN***—Synchronize sequence numbers to initiate a connection; see Chapter 13.
8. ***FIN***—The sender of the segment is finished sending data to its peer; see Chapter 13.

TCP's flow control is provided by each end advertising a window size using the *Window Size* field. This is the number of bytes, starting with the one specified by the ACK number, that the receiver is willing to accept. This is a 16-bit field, limiting the window to 65,535 bytes, and thereby limiting TCP's throughput performance. In Chapter 15 we will look at the Window Scale option that allows this value to be scaled, providing much larger windows and improved performance for high-speed and long-delay networks.

The *TCP Checksum* field covers the TCP header and data and some fields in the IP header, using a pseudo-header computation similar to the one used with ICMPv6 and UDP that we discussed in Chapters 8 and 10. It is mandatory for this field to be calculated and stored by the sender, and then verified by the receiver. The TCP checksum is calculated with the same algorithm as the IP, ICMP, and UDP ("Internet") checksums.

The *Urgent Pointer* field is valid only if the *URG* bit field is set. This "pointer" is a positive offset that must be added to the *Sequence Number* field of the segment to yield the sequence number of the *last* byte of urgent data. TCP's urgent mechanism is a way for the sender to provide specially marked data to the other end.

The most common *Option* field is the Maximum Segment Size option, called the MSS. Each end of a connection normally specifies this option on the first segment it sends (the ones with the *SYN* bit field set to establish the connection). The MSS option specifies the maximum-size segment that the sender of the option is willing to receive in the reverse direction. We describe the MSS option in more detail in Chapter 13 and some of the other TCP options in Chapters 14 and 15. Other common options we investigate include SACK, Timestamp, and Window Scale.

In Figure 12-2 we note that the data portion of the TCP segment is optional. We will see in Chapter 13 that when a connection is established, and when a connection is terminated, segments are exchanged that contain only the TCP header (with or without options) but no data. A header without any data is also used to acknowledge received data, if there is no data to be transmitted in that direction (called a *pure ACK*), and to notify the communication peer of a change in the window size (called a *window update*). There are also some cases resulting from timeouts when a segment can be sent without any data.

12.4 Summary

The problem of providing reliable communications over lossy communication channels has been studied for years. The two primary methods for dealing with errors include error-correcting codes and data retransmission. The protocols using retransmissions must also handle data loss, usually by setting a timer, and must also arrange some way for the receiver to signal the sender what it has received. Deciding how long to wait for an ACK can be tricky, as the appropriate time may change as network routing or load on the end systems varies. Modern protocols estimate the round-trip time and set the retransmission timer based on some function of these measurements.

Except for setting the retransmission timer, retransmission protocols are simple when only one packet may be in the network at one time, but they perform poorly for networks where the delay is high. To be more efficient, multiple packets must be injected into the network before an ACK is received. This approach is more efficient but also more complex. A typical approach to managing the complexity is to use sliding windows, whereby packets are marked with sequence numbers, and the window size bounds the number of such packets. When the window size varies based on either feedback from the receiver or other signals (such as dropped packets), both flow control and congestion control can be achieved.

TCP provides a reliable, connection-oriented, byte stream, transport-layer service built using many of these techniques. We looked briefly at all of the fields in the TCP header, noting that most of them are directly related to these abstract concepts in reliable delivery. We will examine them in detail in the chapters that follow. TCP packetizes the application data into segments, sets a timeout anytime it sends data, acknowledges data received by the other end, reorders out-of-order data, discards duplicate data, provides end-to-end flow control, and calculates and verifies a mandatory end-to-end checksum. It is the most widely used protocol on the Internet. It is used by most of the popular applications, such as HTTP, SSH/TLS, NetBIOS (NBT—NetBIOS over TCP), Telnet, FTP, and electronic mail (SMTP). Many distributed file-sharing applications (e.g., BitTorrent, Shareaza) also use TCP.

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