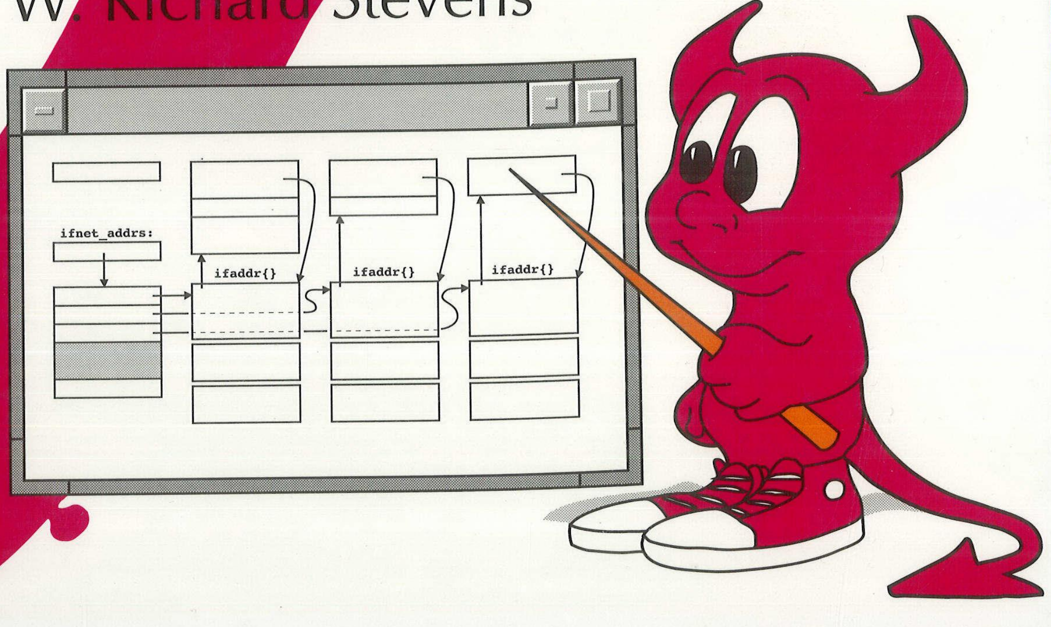
TCP/IP Illustrated, Volume 2

The Implementation

Gary R. Wright
W. Richard Stevens



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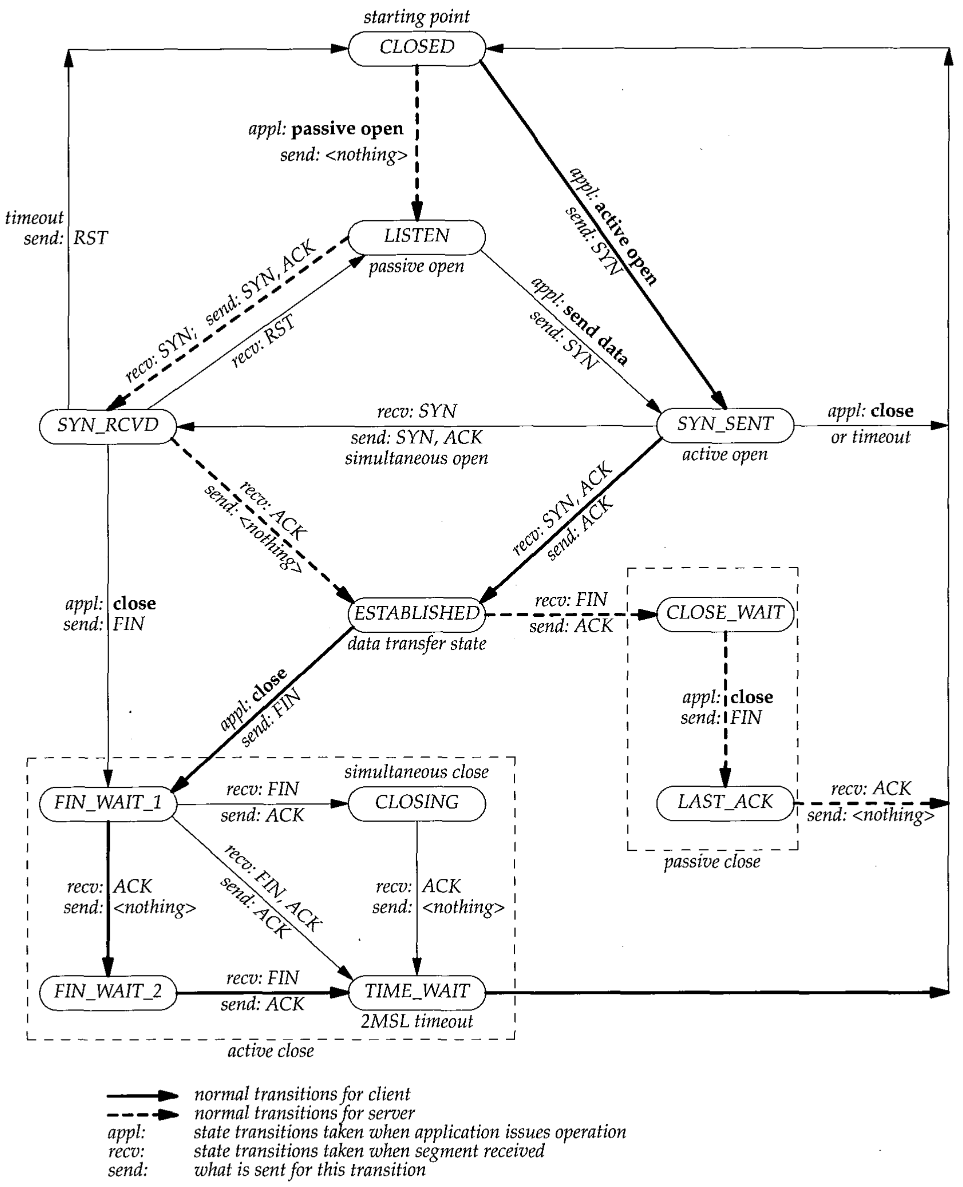

TCP state transition diagram.

INTEL EX.1095.002

Structure Definitions

arpcom	80	mrt	419
arphdr	682	mrtctl	420
		msghdr	482
bpf_d	1033		
bpf_hdr	1029	osockaddr	75
bpf_if	1029		
		pdevinit	78
cmsghdr	482	protosw	188
domain	187	radix_mask	578
		radix_node	575
ether_arp	682	radix_node_head	574
ether_header	102	rawcb	647
ether_multi	342	route	220
		route_cb	625
icmp	308	rt_addrinfo	623
ifaddr	73	rtentry	579
ifa_msghdr	622	rt_metrics	580
ifconf	117	rt_msghdr	622
if_msghdr	622		
ifnet	67	selinfo	531
ifqueue	71	sl_softc	83
ifreq	117	sockaddr	75
igmp	384	sockaddr_dl	87
in_addr	160	sockaddr_in	160
in_aliasreq	174	sockaddr_inarp	701
in_ifaddr	161	sockbuf	476
in_multi	345	socket	438
inpcb	716	socket_args	444
iovec	481	sockproto	626
ip	211	sysent	443
ipasfrag	287		
ip_moptions	347	tcpcb	804
ip_mreq	356	tcp_debug	916
ipoption	265	tcphdr	801
ipovly	760	tcpiphdr	803
ipq	286	timeval	106
ip_srcrt	258		
ip_timestamp	262	udphdr	759
		udpiphdr	759
le_softc	80	uio	485
lgrplctl	411		
linger	542	vif	406
llinfo_arp	682	vifctl	407
mbuf	38	walkarg	632

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To my parents and my sister,
for their love and support.
—G.R.W.

To my parents,
for the gift of an education,
and the example of a work ethic.
—W.R.S.

Contents

Preface

Introduction

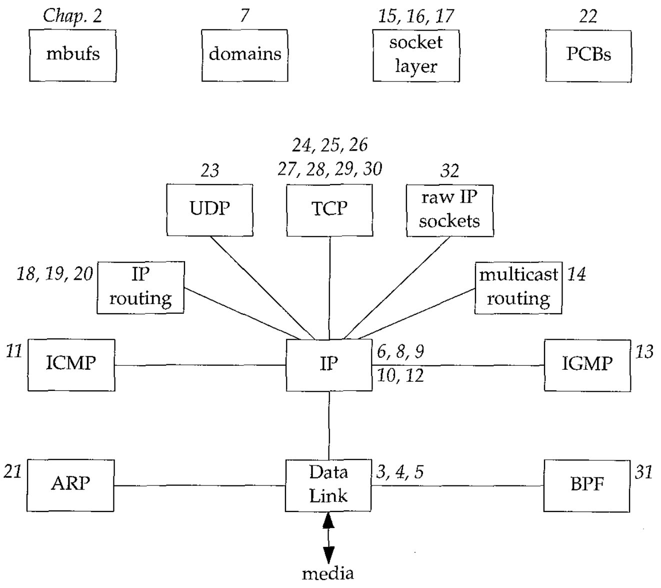
This book describes and presents the source code for the common reference implementation of TCP/IP: the implementation from the Computer Systems Research Group (CSRG) at the University of California at Berkeley. Historically this has been distributed with the 4.x BSD system (Berkeley Software Distribution). This implementation was first released in 1982 and has survived many significant changes, much fine tuning, and numerous ports to other Unix and non-Unix systems. This is not a toy implementation, but the foundation for TCP/IP implementations that are run daily on hundreds of thousands of systems worldwide. This implementation also provides router functionality, letting us show the differences between a host implementation of TCP/IP and a router.

We describe the implementation and present the entire source code for the kernel implementation of TCP/IP, approximately 15,000 lines of C code. The version of the Berkeley code described in this text is the 4.4BSD-Lite release. This code was made publicly available in April 1994, and it contains numerous networking enhancements that were added to the 4.3BSD Tahoe release in 1988, the 4.3BSD Reno release in 1990, and the 4.4BSD release in 1993. (Appendix B describes how to obtain this source code.) The 4.4BSD release provides the latest TCP/IP features, such as multicasting and long fat pipe support (for high-bandwidth, long-delay paths). Figure 1.1 (p. 4) provides additional details of the various releases of the Berkeley networking code.

This book is intended for anyone wishing to understand how the TCP/IP protocols are implemented: programmers writing network applications, system administrators responsible for maintaining computer systems and networks utilizing TCP/IP, and any programmer interested in understanding how a large body of nontrivial code fits into a real operating system.

Organization of the Book

The following figure shows the various protocols and subsystems that are covered. The italic numbers by each box indicate the chapters in which that topic is described.



We take a bottom-up approach to the TCP/IP protocol suite, starting at the data-link layer, then the network layer (IP, ICMP, IGMP, IP routing, and multicast routing), followed by the socket layer, and finishing with the transport layer (UDP, TCP, and raw IP).

Intended Audience

This book assumes a basic understanding of how the TCP/IP protocols work. Readers unfamiliar with TCP/IP should consult the first volume in this series, [Stevens 1994], for a thorough description of the TCP/IP protocol suite. This earlier volume is referred to throughout the current text as *Volume 1*. The current text also assumes a basic understanding of operating system principles.

We describe the implementation of the protocols using a data-structures approach. That is, in addition to the source code presentation, each chapter contains pictures and descriptions of the data structures used and maintained by the source code. We show how these data structures fit into the other data structures used by TCP/IP and the kernel. Heavy use is made of diagrams throughout the text—there are over 250 diagrams.

This data-structures approach allows readers to use the book in various ways. Those interested in all the implementation details can read the entire text from start to finish, following through all the source code. Others might want to understand how the protocols are implemented by understanding all the data structures and reading all the text, but not following through all the source code.

We anticipate that many readers are interested in specific portions of the book and will want to go directly to those chapters. Therefore many forward and backward references are provided throughout the text, along with a thorough index, to allow individual chapters to be studied by themselves. The inside back covers contain an alphabetical cross-reference of all the functions and macros described in the book and the starting page number of the description. Exercises are provided at the end of the chapters; most solutions are in Appendix A to maximize the usefulness of the text as a self-study reference.

Source Code Copyright

All of the source code presented in this book, other than Figures 1.2 and 8.27, is from the 4.4BSD-Lite distribution. This software is publicly available through many sources (Appendix B).

All of this source code contains the following copyright notice.

```
/*
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 *
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 * OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF
 * SUCH DAMAGE.
 */
```

Acknowledgments

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W.R.S. thanks his family, once again, for enduring another "small" book project. Thank you Sally, Bill, Ellen, and David.

The hardwork, professionalism, and support of the team at Addison-Wesley has made the authors' job that much easier. In particular, we wish to thank John Wait for his guidance and Kim Dawley for her creative ideas.

Camera-ready copy of the book was produced by the authors. It is only fitting that a book describing an industrial-strength software system be produced with an industrial-strength text processing system. Therefore one of the authors chose to use the Groff package written by James Clark, and the other author agreed begrudgingly.

We welcome electronic mail from any readers with comments, suggestions, or bug fixes: `tcpipiv2-book@aw.com`. Each author will gladly blame the other for any remaining errors.

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November 1994

1

Introduction

1.1 Introduction

This chapter provides an introduction to the Berkeley networking code. We start with a description of the source code presentation and the various typographical conventions used throughout the text. A quick history of the various releases of the code then lets us see where the source code shown in this book fits in. This is followed by a description of the two predominant programming interfaces used under both Unix and non-Unix systems to write programs that use the TCP/IP protocols.

We then show a simple user program that sends a UDP datagram to the daytime server on another host on the local area network, causing the server to return a UDP datagram with the current time and date on the server as a string of ASCII text. We follow the datagram sent by the process all the way down the protocol stack to the device driver, and then follow the reply received from server all the way up the protocol stack to the process. This trivial example lets us introduce many of the kernel data structures and concepts that are described in detail in later chapters.

The chapter finishes with a look at the organization of the source code that is presented in the book and a review of where the networking code fits in the overall organization.

1.2 Source Code Presentation

Presenting 15,000 lines of source code, regardless of the topic, is a challenge in itself. The following format is used for all the source code in the text:

tcp_subr.c

```
381 void
382 tcp_quench(inp, errno)
383 struct inpcb *inp;
384 int     errno;
385 {
386     struct tcpcb *tp = intotcpcb(inp);

387     if (tp)
388         tp->snd_cwnd = tp->t_maxseg;
389 }
```

tcp_subr.c

Set congestion window to one segment

387–388 This is the `tcp_quench` function from the file `tcp_subr.c`. These source filenames refer to files in the 4.4BSD-Lite distribution, which we describe in Section 1.13. Each nonblank line is numbered. The text describing portions of the code begins with the starting and ending line numbers in the left margin, as shown with this paragraph. Sometimes the paragraph is preceded by a short descriptive heading, providing a summary statement of the code being described.

The source code has been left as is from the 4.4BSD-Lite distribution, including occasional bugs, which we note and discuss when encountered, and occasional editorial comments from the original authors. The code has been run through the GNU Indent program to provide consistency in appearance. The tab stops have been set to four-column boundaries to allow the lines to fit on a page. Some `#ifdef` statements and their corresponding `#endif` have been removed when the constant is always defined (e.g., `GATEWAY` and `MROUTING`, since we assume the system is operating as a router and as a multicast router). All `register` specifiers have been removed. Sometimes a comment has been added and typographical errors in the comments have been fixed, but otherwise the code has been left alone.

The functions vary in size from a few lines (`tcp_quench` shown earlier) to `tcp_input`, which is the biggest at 1100 lines. Functions that exceed about 40 lines are normally broken into pieces, which are shown one after the other. Every attempt is made to place the code and its accompanying description on the same page or on facing pages, but this isn't always possible without wasting a large amount of paper.

Many cross-references are provided to other functions that are described in the text. To avoid appending both a figure number and a page number to each reference, the inside back covers contain an alphabetical cross-reference of all the functions and macros described in the book, and the starting page number of the description. Since the source code in the book is taken from the publicly available 4.4BSD-Lite release, you can easily obtain a copy: Appendix B details various ways. Sometimes it helps to have an on-line copy to search through [e.g., with the Unix `grep`(1) program] as you follow the text.

Each chapter that describes a source code module normally begins with a listing of the source files being described, followed by the global variables, the relevant statistics maintained by the code, some sample statistics from an actual system, and finally the SNMP variables related to the protocol being described. The global variables are often defined across various source files and headers, so we collect them in one table for easy reference. Showing all the statistics at this point simplifies the later discussion of the code when the statistics are updated. Chapter 25 of Volume 1 provides all the details on SNMP. Our interest in this text is in the information maintained by the TCP/IP routines in the kernel to support an SNMP agent running on the system.

Typographical Conventions

In the figures throughout the text we use a constant-width font for variable names and the names of structure members (`m_next`), a slanted constant-width font for names that are defined constants (*`NULL`*) or constant values (*`512`*), and a bold constant-width font with braces for structure names (**`mbuf{}`**). Here is an example:

`mbuf{}`

`m_next`	*`NULL`*
`m_len`	*`512`*

In tables we use a constant-width font for variable names and the names of structure members, and the slanted constant-width font for the names of defined constants. Here is an example:

`m_flags`	Description
`M_BCAST`	sent/received as link-level broadcast

We normally show all `#define` symbols this way. We show the value of the symbol if necessary (the value of `M_BCAST` is irrelevant) and sort the symbols alphabetically, unless some other ordering makes sense.

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

We refer to Unix commands using the name of the command followed by a number in parentheses, as in `grep`(1). The number in parentheses is the section number in the 4.4BSD manual of the "manual page" for the command, where additional information can be located.

1.3 History

This book describes the common reference implementation of TCP/IP from the Computer Systems Research Group at the University of California at Berkeley. Historically this has been distributed with the 4.x BSD system (Berkeley Software Distribution) and with the "BSD Networking Releases." This source code has been the starting point for many other implementations, both for Unix and non-Unix operating systems.

Figure 1.1 shows a chronology of the various BSD releases, indicating the important TCP/IP features. The releases shown on the left side are publicly available source code releases containing all of the networking code: the protocols themselves, the kernel

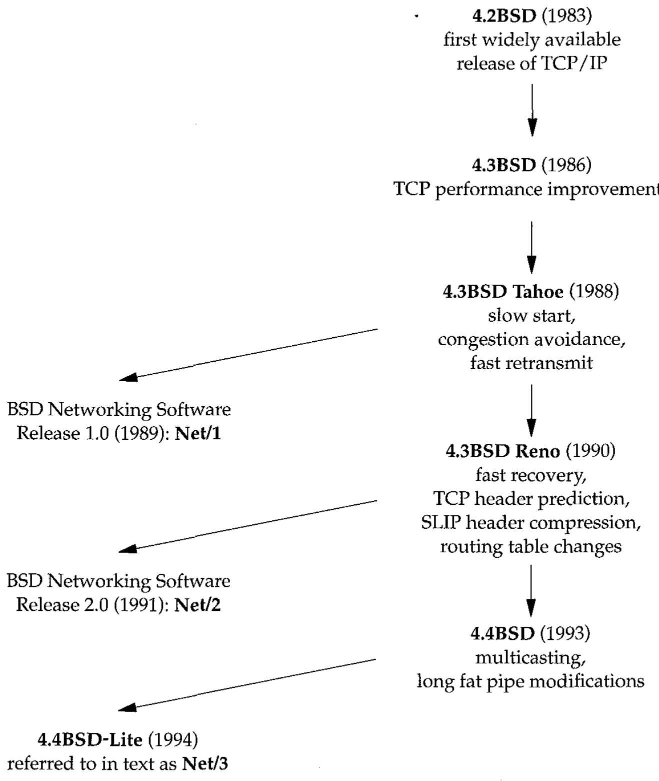


Figure 1.1 Various BSD releases with important TCP/IP features.

routines for the networking interface, and many of the applications and utilities (such as Telnet and FTP).

Although the official name of the software described in this text is the *4.4BSD-Lite* distribution, we'll refer to it simply as *Net/3.*

While the source code is distributed by U. C. Berkeley and is called the *Berkeley Software Distribution*, the TCP/IP code is really the merger and consolidation of the works of various researchers, both at Berkeley and at other locations.

Throughout the text we'll use the term *Berkeley-derived implementation* to refer to vendor implementations such as SunOS 4.x, System V Release 4 (SVR4), and AIX 3.2, whose TCP/IP code was originally developed from the Berkeley sources. These implementations have much in common, often including the same bugs!

Not shown in Figure 1.1 is that the first release with the Berkeley networking code was actually 4.1cBSD in 1982. 4.2BSD, however, was the widely released version in 1983.

BSD releases prior to 4.1cBSD used a TCP/IP implementation developed at Bolt Beranek and Newman (BBN) by Rob Gurwitz and Jack Haverty. Chapter 18 of [Salus 1994] provides additional details on the incorporation of the BBN code into 4.2BSD. Another influence on the Berkeley TCP/IP code was the TCP/IP implementation done by Mike Muuss at the Ballistics Research Lab for the PDP-11.

Limited documentation exists on the changes in the networking code from one release to the next. [Karels and McKusick 1986] describe the changes from 4.2BSD to 4.3BSD, and [Jacobson 1990d] describes the changes from 4.3BSD Tahoe to 4.3BSD Reno.

1.4 Application Programming Interfaces

Two popular *application programming interfaces* (APIs) for writing programs to use the Internet protocols are *sockets* and *TLI* (Transport Layer Interface). The former is sometimes called *Berkeley sockets*, since it was widely released with the 4.2BSD system (Figure 1.1). It has, however, been ported to many non-BSD Unix systems and many non-Unix systems. The latter, originally developed by AT&T, is sometimes called *XTI* (X/Open Transport Interface) in recognition of the work done by X/Open, an international group of computer vendors who produce their own set of standards. XTI is effectively a superset of TLI.

This is not a programming text, but we describe the sockets interface since sockets are used by applications to access TCP/IP in Net/3 (and in all other BSD releases). The sockets interface has also been implemented on a wide variety of non-Unix systems. The programming details for both sockets and TLI are available in [Stevens 1990].

System V Release 4 (SVR4) also provides a sockets API for applications to use, although the implementation differs from what we present in this text. Sockets in SVR4 are based on the "streams" subsystem that is described in [Rago 1993].

1.5 Example Program

We'll use the simple C program shown in Figure 1.2 to introduce many features of the BSD networking implementation in this chapter.

```
 1 /*
 2  * Send a UDP datagram to the daytime server on some other host,
 3  * read the reply, and print the time and date on the server.
 4  */

 5 #include    <sys/types.h>
 6 #include    <sys/socket.h>
 7 #include    <netinet/in.h>
 8 #include    <arpa/inet.h>
 9 #include    <stdio.h>
10 #include    <stdlib.h>
11 #include    <string.h>

12 #define BUFFSIZE    150         /* arbitrary size */
```

```
13 int
14 main()
15 {
16     struct sockaddr_in serv;
17     char    buff[BUFFSIZE];
18     int     sockfd, n;

19     if ((sockfd = socket(PF_INET, SOCK_DGRAM, 0)) < 0)
20         err_sys("socket error");

21     bzero((char *) &serv, sizeof(serv));
22     serv.sin_family = AF_INET;
23     serv.sin_addr.s_addr = inet_addr("140.252.1.32");
24     serv.sin_port = htons(13);

25     if (sendto(sockfd, buff, BUFFSIZE, 0,
26                (struct sockaddr *) &serv, sizeof(serv)) != BUFFSIZE)
27         err_sys("sendto error");

28     if ((n = recvfrom(sockfd, buff, BUFFSIZE, 0,
29                       (struct sockaddr *) NULL, (int *) NULL)) < 2)
30         err_sys("recvfrom error");
31     buff[n - 2] = 0;             /* null terminate */
32     printf("%s\n", buff);

33     exit(0);
34 }
```

Figure 1.2 Example program: send a datagram to the UDP daytime server and read a response.

Create a datagram socket

19–20 `socket` creates a UDP socket and returns a descriptor to the process, which is stored in the variable `sockfd`. The error-handling function `err_sys` is shown in Appendix B.2 of [Stevens 1992]. It accepts any number of arguments, formats them using `vsprintf`, prints the Unix error message corresponding to the `errno` value from the system call, and then terminates the process.

We've now used the term *socket* in three different ways. (1) The API developed for 4.2BSD to allow programs to access the networking protocols is normally called the *sockets API* or just the *sockets interface*. (2) `socket` is the name of a function in the sockets API. (3) We refer to the end point created by the call to `socket` as a socket, as in the comment "create a datagram socket."

Unfortunately, there are still more uses of the term *socket*. (4) The return value from the `socket` function is called a *socket descriptor* or just a *socket*. (5) The Berkeley implementation of the networking protocols within the kernel is called the *sockets implementation*, compared to the System V streams implementation, for example. (6) The combination of an IP address and a port number is often called a socket, and a pair of IP addresses and port numbers is called a *socket pair*. Fortunately, it is usually obvious from the discussion what the term *socket* refers to.

Fill in `sockaddr_in` structure with server's address

21–24 An Internet socket address structure (`sockaddr_in`) is filled in with the IP address (140.252.1.32) and port number (13) of the daytime server. Port number 13 is the standard Internet daytime server, provided by most TCP/IP implementations [Stevens 1994, Fig. 1.9]. Our choice of the server host is arbitrary—we just picked a local host (Figure 1.17) that provides the service.

The function `inet_addr` takes an ASCII character string representing a *dotted-decimal* IP address and converts it into a 32-bit binary integer in the network byte order. (The network byte order for the Internet protocol suite is big endian. [Stevens 1990, Chap. 4] discusses host and network byte order, and little versus big endian.) The function `htons` takes a short integer in the host byte order (which could be little endian or big endian) and converts it into the network byte order (big endian). On a system such as a Sparc, which uses big endian format for integers, `htons` is typically a macro that does nothing. In BSD/386, however, on the little endian 80386, `htons` can be either a macro or a function that swaps the 2 bytes in a 16-bit integer.

Send datagram to server

25–27 The program then calls `sendto`, which sends a 150-byte datagram to the server. The contents of the 150-byte buffer are indeterminate since it is an uninitialized array allocated on the run-time stack, but that's OK for this example because the server never looks at the contents of the datagram that it receives. When the server receives a datagram it sends a reply to the client. The reply contains the current time and date on the server in a human-readable format.

Our choice of 150 bytes for the client's datagram is arbitrary. We purposely pick a value greater than 100 and less than 208 to show the use of an mbuf chain later in this chapter. We also want a value less than 1472 to avoid fragmentation on an Ethernet.

Read datagram returned by server

28–32 The program reads the datagram that the server sends back by calling `recvfrom`. Unix servers typically send back a 26-byte string of the form

```
Sat Dec 11 11:28:05 1993\r\n
```

where `\r` is an ASCII carriage return and `\n` is an ASCII linefeed. Our program overwrites the carriage return with a null byte and calls `printf` to output the result.

We go into lots of detail about various parts of this example in this and later chapters as we examine the implementation of the functions `socket`, `sendto`, and `recvfrom`.

1.6 System Calls and Library Functions

All operating systems provide service points through which programs request services from the kernel. All variants of Unix provide a well-defined, limited number of kernel entry points known as *system calls*. We cannot change the system calls unless we have the kernel source code. Unix Version 7 provided about 50 system calls, 4.4BSD provides about 135, and SVR4 has around 120.

The system call interface is documented in Section 2 of the *Unix Programmer's Manual*. Its definition is in the C language, regardless of how system calls are invoked on any given system.

The Unix technique is for each system call to have a function of the same name in the standard C library. An application calls this function, using the standard C calling sequence. This function then invokes the appropriate kernel service, using whatever technique is required on the system. For example, the function may put one or more of the C arguments into general registers and then execute some machine instruction that generates a software interrupt into the kernel. For our purposes, we can consider the system calls to be C functions.

Section 3 of the *Unix Programmer's Manual* defines the general purpose functions available to programmers. These functions are not entry points into the kernel, although they may invoke one or more of the kernel's system calls. For example, the `printf` function may invoke the `write` system call to perform the output, but the functions `strcpy` (copy a string) and `atoi` (convert ASCII to integer) don't involve the operating system at all.

From an implementor's point of view, the distinction between a system call and a library function is fundamental. From a user's perspective, however, the difference is not as critical. For example, if we run Figure 1.2 under 4.4BSD, when the program calls the three functions `socket`, `sendto`, and `recvfrom`, each ends up calling a function of the same name within the kernel. We show the BSD kernel implementation of these three system calls later in the text.

If we run the program under SVR4, where the socket functions are in a user library that calls the "streams" subsystem, the interaction of these three functions with the kernel is completely different. Under SVR4 the call to `socket` ends up invoking the kernel's `open` system call for the file `/dev/udp` and then pushes the streams module `sockmod` onto the resulting stream. The call to `sendto` results in a `putmsg` system call, and the call to `recvfrom` results in a `getmsg` system call. These SVR4 details are not critical in this text. We want to point out only that the implementation can be totally different while providing the same API to the application.

This difference in implementation technique also accounts for the manual page for the `socket` function appearing in Section 2 of the 4.4BSD manual but in Section 3n (the letter *n* stands for the networking subsection of Section 3) of the SVR4 manuals.

Finally, the implementation technique can change from one release to the next. For example, in Net/1 `send` and `sendto` were implemented as separate system calls within the kernel. In Net/3, however, `send` is a library function that calls `sendto`, which is a system call:

```
send(int s, char *msg, int len, int flags)
{
    return(sendto(s, msg, len, flags, (struct sockaddr *) NULL, 0));
}
```

The advantage in implementing `send` as a library function that just calls `sendto` is a reduction in the number of system calls and in the amount of code within the kernel. The disadvantage is the additional overhead of one more function call for the process that calls `send`.

Since this text describes the Berkeley implementation of TCP/IP, most of the functions called by the process (`socket`, `bind`, `connect`, etc.) are implemented directly in the kernel as system calls.

1.7 Network Implementation Overview

Net/3 provides a general purpose infrastructure capable of simultaneously supporting multiple communication protocols. Indeed, 4.4BSD supports four distinct communication protocol families:

1. TCP/IP (the Internet protocol suite), the topic of this book.
2. XNS (Xerox Network Systems), a protocol suite that is similar to TCP/IP; it was popular in the mid-1980s for connecting Xerox hardware (such as printers and file servers), often using an Ethernet. Although the code is still distributed with Net/3, few people use this protocol suite today, and many vendors who use the Berkeley TCP/IP code remove the XNS code (so they don't have to support it).
3. The OSI protocols [Rose 1990; Piscitello and Chapin 1993]. These protocols were designed during the 1980s as the ultimate in open-systems technology, to replace all other communication protocols. Their appeal waned during the early 1990s, and as of this writing their use in real networks is minimal. Their place in history is still to be determined.
4. The Unix domain protocols. These do not form a true protocol suite in the sense of communication protocols used to exchange information between different systems, but are provided as a form of *interprocess communication* (IPC).

   The advantage in using the Unix domain protocols for IPC between two processes on the same host, versus other forms of IPC such as System V message queues [Stevens 1990], is that the Unix domain protocols are accessed using the same API (sockets) as are the other three communication protocols. Message queues, on the other hand, and most other forms of IPC, have an API that is completely different from both sockets and TLI. Having IPC between two processes on the same host use the networking API makes it easy to migrate a client–server application from one host to many hosts. Two different protocols are provided in the Unix domain—a reliable, connection-oriented, byte-stream protocol that looks like TCP, and an unreliable, connectionless, datagram protocol that looks like UDP.

   Although the Unix domain protocols can be used as a form of IPC between two processes on the same host, these processes could also use TCP/IP to communicate with each other. There is no requirement that processes communicating using the Internet protocols reside on different hosts.

The networking code in the kernel is organized into three layers, as shown in Figure 1.3. On the right side of this figure we note where the seven layers of the OSI reference model [Piscitello and Chapin 1994] fit in the BSD organization.

1. The *socket layer* is a protocol-independent interface to the protocol-dependent layer below. All system calls start at the protocol-independent socket layer. For example, the protocol-independent code in the socket layer for the `bind` system call comprises a few dozen lines of code: these verify that the first argument is a

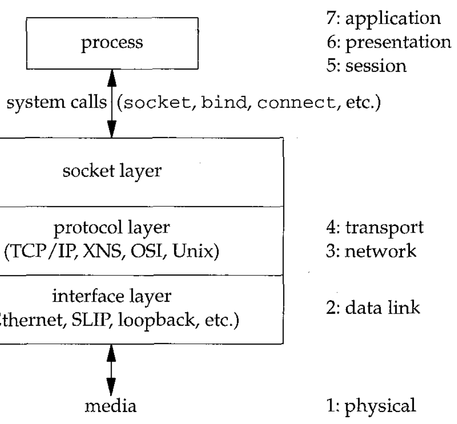


Figure 1.3 The general organization of networking code in Net/3.

valid socket descriptor and that the second argument is a valid pointer in the process. The protocol-dependent code in the layer below is then called, which might comprise hundreds of lines of code.

2. The *protocol layer* contains the implementation of the four protocol families that we mentioned earlier (TCP/IP, XNS, OSI, and Unix domain). Each protocol suite may have its own internal structure, which we don't show in Figure 1.3. For example, in the Internet protocol suite, IP is the lowest layer (the network layer) with the two transport layers (TCP and UDP) above IP.
3. The *interface layer* contains the device drivers that communicate with the network devices.

1.8 Descriptors

Figure 1.2 begins with a call to `socket`, specifying the type of socket desired. The combination of the Internet protocol family (`PF_INET`) and a datagram socket (`SOCK_DGRAM`) gives a socket whose protocol is UDP.

The return value from `socket` is a descriptor that shares all the properties of other Unix descriptors: `read` and `write` can be called for the descriptor, you can `dup` it, it is shared by the parent and child after a call to `fork`, its properties can be modified by calling `fcntl`, it can be closed by calling `close`, and so on. We see in our example that the socket descriptor is the first argument to both the `sendto` and `recvfrom` functions. When our program terminates (by calling `exit`), all open descriptors including the socket descriptor are closed by the kernel.

We now introduce the data structures that are created by the kernel when the process calls `socket`. We describe these data structures in more detail in later chapters.

Everything starts with the process table entry for the process. One of these exists for each process during its lifetime.

A descriptor is an index into an array within the process table entry for the process. This array entry points to an open file table structure, which in turn points to an i-node or v-node structure that describes the file. Figure 1.4 summarizes this relationship.

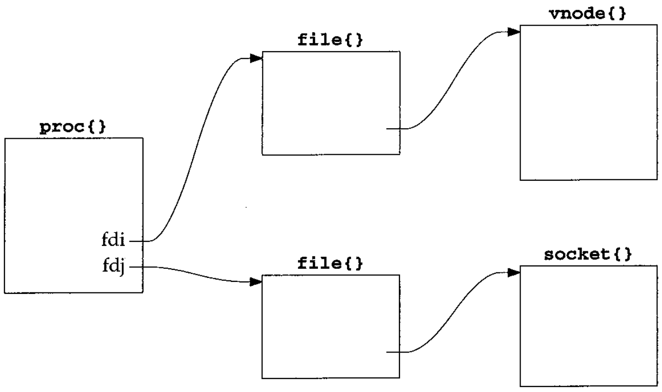


Figure 1.4 Fundamental relationship between kernel data structures starting with a descriptor.

In this figure we also show a descriptor that refers to a socket, which is the focus of this text. We place the notation `proc{}` above the process table entry, since its definition in C is

```
struct proc {
    ...
}
```

and we use this notation for structures in our figures throughout the text.

[Stevens 1992, Sec. 3.10] shows how the relationships between the descriptor, file table structure, and i-node or v-node change as the process calls `dup` and `fork`. The relationships between these three data structures exists in all versions of Unix, although the details change with different implementations. Our interest in this text is with the `socket` structure and the Internet-specific data structures that it points to. But we need to understand how a descriptor leads to a `socket` structure, since the socket system calls start with a descriptor.

Figure 1.5 shows more details of the Net/3 data structures for our example program, if the program is executed as

```
a.out
```

without redirecting standard input (descriptor 0), standard output (descriptor 1), or standard error (descriptor 2). In this example, descriptors 0, 1, and 2 are connected to our terminal, and the lowest-numbered unused descriptor is 3 when `socket` is called.

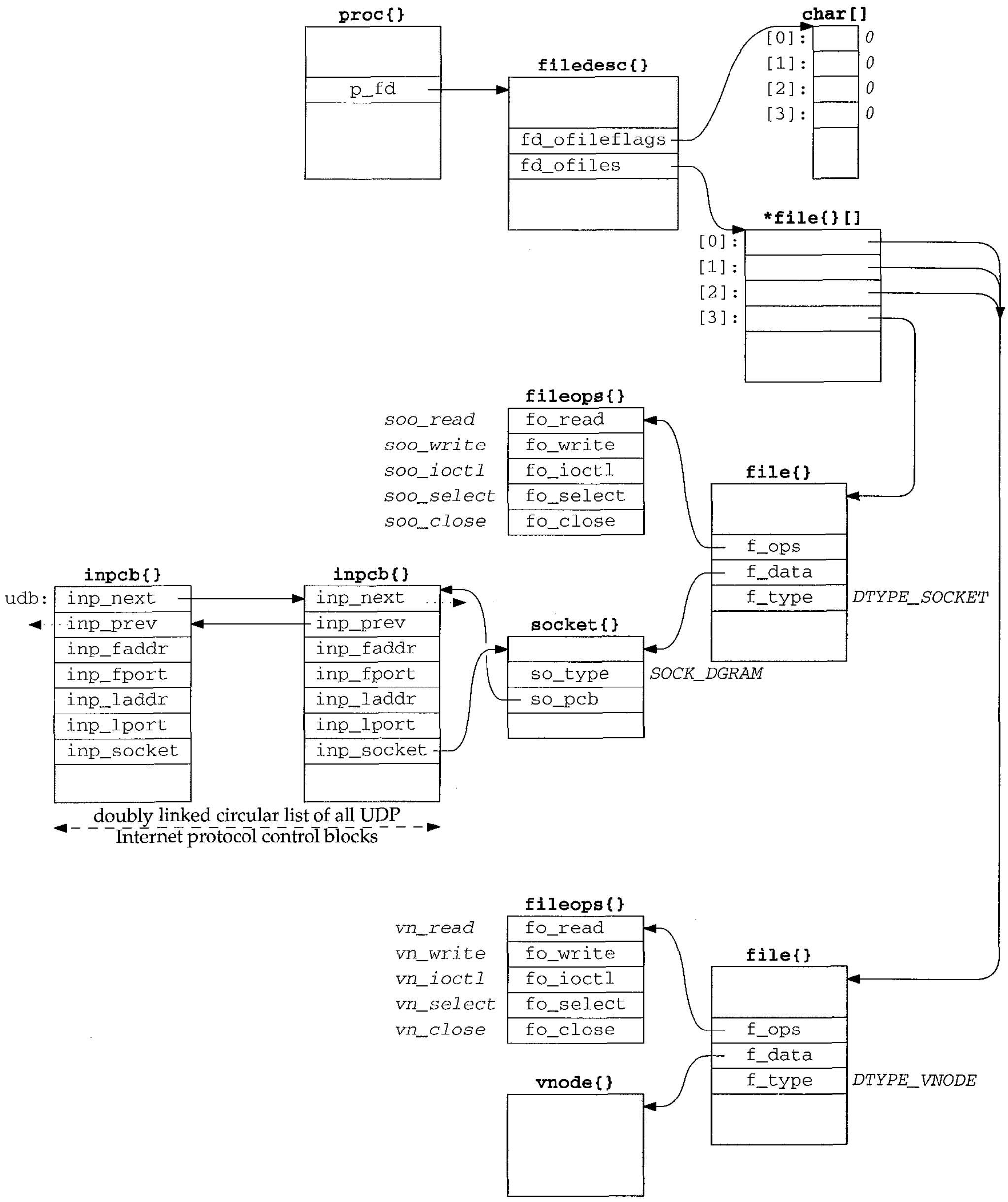


Figure 1.5 Kernel data structures after call to socket in example program.

When a process executes a system call such as socket, the kernel has access to the process table structure. The entry p_fd in this structure points to the filedesc structure for the process. There are two members of this structure that interest us now: fd_ofileflags is a pointer to an array of characters (the per-descriptor flags for each descriptor), and fd_ofiles is a pointer to an array of pointers to file table structures. The per-descriptor flags are 8 bits wide since only 2 bits can be set for any descriptor: the close-on-exec flag and the mapped-from-device flag. We show all these flags as 0.

> We purposely call this section "Descriptors" and not "File Descriptors" since Unix descriptors can refer to lots of things other than files: sockets, pipes, directories, devices, and so on. Nevertheless, much of Unix literature uses the adjective *file* when talking about descriptors, which is an unnecessary qualification. Here the kernel data structure is called filedesc{} even though we're about to describe socket descriptors. We'll use the unqualified term *descriptor* whenever possible.

The data structure pointed to by the fd_ofiles entry is shown as *file{}[] since it is an array of pointers to file structures. The index into this array and the array of descriptor flags is the nonnegative descriptor itself: 0, 1, 2, and so on. In Figure 1.5 we show the entries for descriptors 0, 1, and 2 pointing to the same file structure at the bottom of the figure (since all three descriptors refer to our terminal). The entry for descriptor 3 points to a different file structure for our socket descriptor.

The f_type member of the file structure specifies the descriptor type as either DTYPE_SOCKET or DTYPE_VNODE. V-nodes are a general mechanism that allows the kernel to support different types of filesystems—a disk filesystem, a network filesystem (such as NFS), a filesystem on a CD-ROM, a memory-based filesystem, and so on. Our interest in this text is not with v-nodes, since TCP/IP sockets always have a type of DTYPE_SOCKET.

The f_data member of the file structure points to either a socket structure or a vnode structure, depending on the type of descriptor. The f_ops member points to a vector of five function pointers. These function pointers are used by the read, readv, write, writev, ioctl, select, and close system calls, since these system calls work with either a socket descriptor or a nonsocket descriptor. Rather than look at the f_type value each time one of these system calls is invoked and then jump accordingly, the implementors chose always to jump indirectly through the corresponding entry in the fileops structure instead.

Notationally we use a fixed-width font (fo_read) to show the name of a structure member and a slanted fixed-width font (*soo_read*) to show the contents of a structure member. Also note that sometimes we show the pointer to a structure arriving at the top left corner (e.g., the filedesc structure) and sometimes at the top right corner (e.g., both file structures and both fileops structures). This is to simplify the figures.

Next we come to the socket structure that is pointed to by the file structure when the descriptor type is DTYPE_SOCKET. In our example, the socket type (SOCK_DGRAM for a datagram socket) is stored in the so_type member. An Internet protocol control block (PCB) is also allocated: an inpcb structure. The so_pcb member of the socket structure points to the inpcb, and the inp_socket member of the inpcb structure points to the socket structure. Each points to the other because the activity for a given socket can occur from two directions: "above" or "below."

1. When the process executes a system call, such as sendto, the kernel starts with the descriptor value and uses fd_ofiles to index into the vector of file structure pointers, ending up with the file structure for the descriptor. The file structure points to the socket structure, which points to the inpcb structure.
2. When a UDP datagram arrives on a network interface, the kernel searches through all the UDP protocol control blocks to find the appropriate one, minimally based on the destination UDP port number and perhaps the destination IP address, source IP address, and source port numbers too. Once the inpcb structure is located, the kernel finds the corresponding socket structure through the inp_socket pointer.

The members inp_faddr and inp_laddr contain the foreign and local IP addresses, and the members inp_fport and inp_lport contain the foreign and local port numbers. The combination of the local IP address and the local port number is often called a *socket*, as is the combination of the foreign IP address and the foreign port number.

We show another inpcb structure with the name udb on the left in Figure 1.5. This is a global structure that is the head of a linked list of all UDP PCBs. We show the two members inp_next and inp_prev that form a doubly linked circular list of all UDP PCBs. For notational simplicity in the figure, we show two parallel horizontal arrows for the two links instead of trying to have the heads of the arrows going to the top corners of the PCBs. The inp_prev member of the inpcb structure on the right points to the udb structure, not the inp_prev member of that structure. The dotted arrows from udb.inp_prev and the inp_next member of the other PCB indicate that there may be other PCBs on the doubly linked list that we don't show.

We've looked at many kernel data structures in this section, most of which are described further in later chapters. The key points to understand now are:

1. The call to socket by our process ends up allocating the lowest unused descriptor (3 in our example). This descriptor is used by the process in all subsequent system calls that refer to this socket.
2. The following kernel structures are allocated and linked together: a file structure of type DTYPE_SOCKET, a socket structure, and an inpcb structure. Lots of initialization is performed on these structures that we don't show: the file structure is marked for read and write (since the call to socket always returns a descriptor that can be read or written), the default sizes of the input and output buffers are set in the socket structure, and so on.
3. We showed nonsocket descriptors for our standard input, output, and error to show that *all* descriptors end up at a file structure, and it is from that point on that differences appear between socket descriptors and other descriptors.

1.9 Mbufs (Memory Buffers) and Output Processing

A fundamental concept in the design of the Berkeley networking code is the memory buffer, called an *mbuf,* used throughout the networking code to hold various pieces of information. Our simple example (Figure 1.2) lets us examine some typical uses of mbufs. In Chapter 2 we describe mbufs in more detail.

Mbuf Containing Socket Address Structure

In the call to sendto, the fifth argument points to an Internet socket address structure (named serv) and the sixth argument specifies its length (which we'll see later is 16 bytes). One of the first things done by the socket layer for this system call is to verify that these arguments are valid (i.e., the pointer points to a piece of memory in the address space of the process) and then copy the socket address structure into an mbuf. Figure 1.6 shows the resulting mbuf.

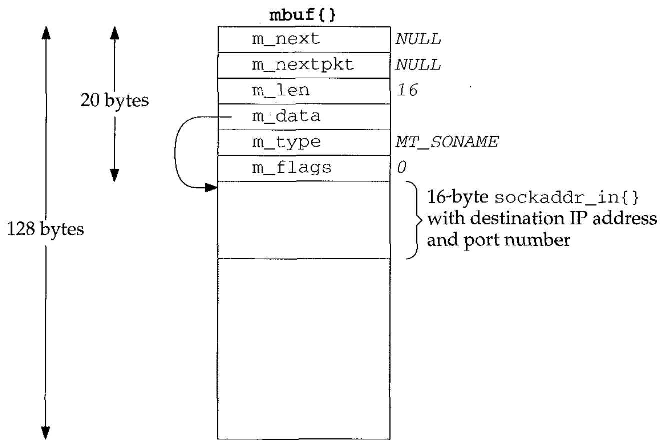


Figure 1.6 Mbuf containing destination address for sendto.

The first 20 bytes of the mbuf is a header containing information about the mbuf. This 20-byte header contains four 4-byte fields and two 2-byte fields. The total size of the mbuf is 128 bytes.

Mbufs can be linked together using the m_next and m_nextpkt members, as we'll see shortly. Both are null pointers in this example, which is a stand-alone mbuf.

The m_data member points to the data in the mbuf and the m_len member specifies its length. For this example, m_data points to the first byte of data in the mbuf (the byte immediately following the mbuf header). The final 92 bytes of the mbuf data area (108 – 16) are unused (the shaded portion of Figure 1.6).

The m_type member specifies the type of data contained in the mbuf, which for this example is MT_SONAME (socket name). The final member in the header, m_flags, is zero in this example.

Mbuf Containing Data

Continuing our example, the socket layer copies the data buffer specified in the call to sendto into one or more mbufs. The second argument to sendto specifies the start of the data buffer (buff), and the third argument is its size in bytes (150). Figure 1.7 shows how two mbufs hold the 150 bytes of data.

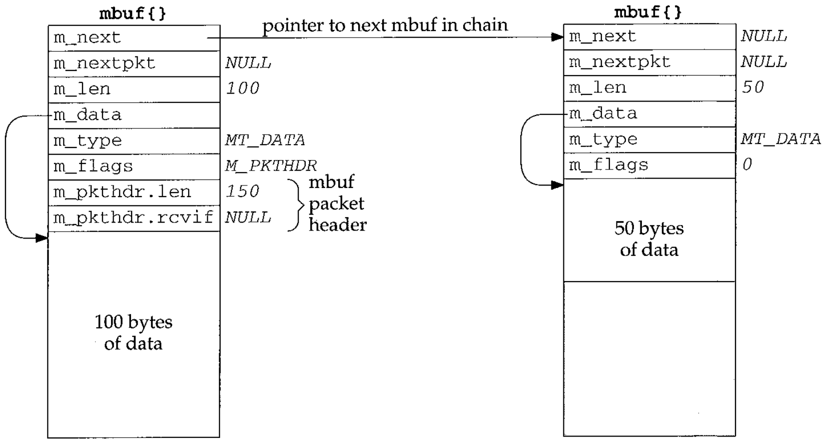


Figure 1.7 Two mbufs holding 150 bytes of data.

This arrangement is called an *mbuf chain*. The m_next member in each mbuf links together all the mbufs in a chain.

The next change we see is the addition of two members, m_pkthdr.len and m_pkthdr.rcvif, to the mbuf header in the first mbuf of the chain. These two members comprise the *packet header* and are used only in the first mbuf of a chain. The m_flags member contains the value M_PKTHDR to indicate that this mbuf contains a packet header. The len member of the packet header structure contains the total length of the mbuf chain (150 in this example), and the next member, rcvif, we'll see later contains a pointer to the received interface structure for received packets.

Since mbufs are *always* 128 bytes, providing 100 bytes of data storage in the first mbuf on the chain and 108 bytes of storage in all subsequent mbufs on the chain, two mbufs are needed to store 150 bytes of data. We'll see later that when the amount of data exceeds 208 bytes, instead of using three or more mbufs, a different technique is used—a larger buffer, typically 1024 or 2048 bytes, called a *cluster* is used.

One reason for maintaining a packet header with the total length in the first mbuf on the chain is to avoid having to go through all the mbufs on the chain to sum their m_len members when the total length is needed.

Prepending IP and UDP Headers

After the socket layer copies the destination socket address structure into an mbuf (Figure 1.6) and the data into an mbuf chain (Figure 1.7), the protocol layer corresponding to the socket descriptor (a UDP socket) is called. Specifically, the UDP output routine is called and pointers to the mbufs that we've examined are passed as arguments. This routine needs to prepend an IP header and a UDP header in front of the 150 bytes of data, fill in the headers, and pass the mbufs to the IP output routine.

The way that data is prepended to the mbuf chain in Figure 1.7 is to allocate another mbuf, make it the front of the chain, and copy the packet header from the mbuf with 100 bytes of data into the new mbuf. This gives us the three mbufs shown in Figure 1.8.

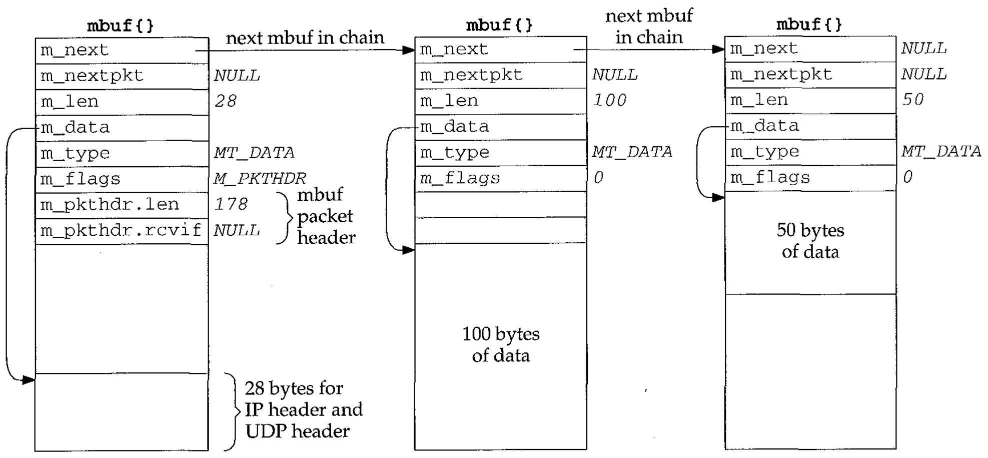


Figure 1.8 Mbuf chain from Figure 1.7 with another mbuf for IP and UDP headers prepended.

The IP header and UDP header are stored at the end of the new mbuf that becomes the head of the chain. This allows for any lower-layer protocols (e.g., the interface layer) to prepend its headers in front of the IP header if necessary, without having to copy the IP and UDP headers. The m_data pointer in the first mbuf points to the start of these two headers, and m_len is 28. Future headers that fit in the 72 bytes of unused space between the packet header and the IP header can be prepended before the IP header by adjusting the m_data pointer and the m_len accordingly. Shortly we'll see that the Ethernet header is built here in this fashion.

Notice that the packet header has been moved from the mbuf with 100 bytes of data into the new mbuf. The packet header must always be in the first mbuf on the chain. To accommodate this movement of the packet header, the M_PKTHDR flag is set in the first mbuf and cleared in the second mbuf. The space previously occupied by the packet header in the second mbuf is now unused. Finally, the length member in the packet header is incremented by 28 bytes to become 178.

The UDP output routine then fills in the UDP header and as much of the IP header as it can. For example, the destination address in the IP header can be set, but the IP checksum will be left for the IP output routine to calculate and store.

The UDP checksum is calculated and stored in the UDP header. Notice that this requires a complete pass of the 150 bytes of data stored in the mbuf chain. So far the kernel has made two complete passes of the 150 bytes of user data: once to copy the data from the user's buffer into the kernel's mbufs, and now to calculate the UDP checksum. Extra passes over the data can degrade the protocol's performance, and in later chapters we describe alternative implementation techniques that avoid unnecessary passes.

At this point the UDP output routine calls the IP output routine, passing a pointer to the mbuf chain for IP to output.

IP Output

The IP output routine fills in the remaining fields in the IP header including the IP checksum, determines the outgoing interface to which the datagram should be given (this is the IP routing function), fragments the IP datagram if necessary, and calls the interface output function.

Assuming the outgoing interface is an Ethernet, a general-purpose Ethernet output function is called, again with a pointer to the mbuf chain as an argument.

Ethernet Output

The first function of the Ethernet output function is to convert the 32-bit IP address into its corresponding 48-bit Ethernet address. This is done using ARP (Address Resolution Protocol) and may involve sending an ARP request on the Ethernet and waiting for an ARP reply. While this takes place, the mbuf chain to be output is held, waiting for the reply.

The Ethernet output routine then prepends a 14-byte Ethernet header to the first mbuf in the chain, immediately before the IP header (Figure 1.8). This contains the 6-byte Ethernet destination address, 6-byte Ethernet source address, and 2-byte Ethernet frame type.

The mbuf chain is then added to the end of the output queue for the interface. If the interface is not currently busy, the interface's "start output" routine is called directly. If the interface is busy, its output routine will process the new mbuf on its queue when it is finished with the buffers already on its output queue.

When the interface processes an mbuf that's on its output queue, it copies the data to its transmit buffer and initiates the output. In our example, 192 bytes are copied to the transmit buffer: the 14-byte Ethernet header, 20-byte IP header, 8-byte UDP header, and 150 bytes of user data. This is the third complete pass of the data by the kernel. Once the data is copied from the mbuf chain into the device's transmit buffer, the mbuf chain is released by the Ethernet device driver. The three mbufs are put back into the kernel's pool of free mbufs.

Summary of UDP Output

In Figure 1.9 we give an overview of the processing that takes place when a process calls `sendto` to transmit a single UDP datagram. The relationship of the processing that we've described to the three layers of kernel code (Figure 1.3) is also shown.

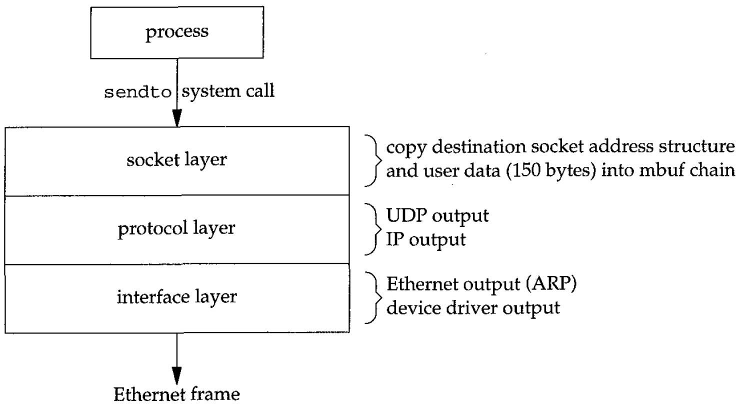


Figure 1.9 Processing performed by the three layers for simple UDP output.

Function calls pass control from the socket layer to the UDP output routine, to the IP output routine, and then to the Ethernet output routine. Each function call passes a pointer to the mbuf chain to be output. At the lowest layer, the device driver, the mbuf chain is placed on the device's output queue and the device is started, if necessary. The function calls return in reverse order of their call, and eventually the system call returns to the process. Notice that there is no queueing of the UDP data until it arrives at the device driver. The higher layers just prepend their header and pass the mbuf to the next lower layer.

At this point our program calls `recvfrom` to read the server's reply. Since the input queue for the specified socket is empty (assuming the reply has not been received yet), the process is put to sleep.

1.10 Input Processing

Input processing is different from the output processing just described because the input is *asynchronous*. That is, the reception of an input packet is triggered by a receive-complete interrupt to the Ethernet device driver, not by a system call issued by the process. The kernel handles this device interrupt and schedules the device driver to run.

Ethernet Input

The Ethernet device driver processes the interrupt and, assuming it signifies a normal receive-complete condition, the data bytes are read from the device into an mbuf chain. In our example, 54 bytes of data are received and copied into a single mbuf: the 20-byte IP header, 8-byte UDP header, and 26 bytes of data (the time and date on the server). Figure 1.10 shows the format of this mbuf.

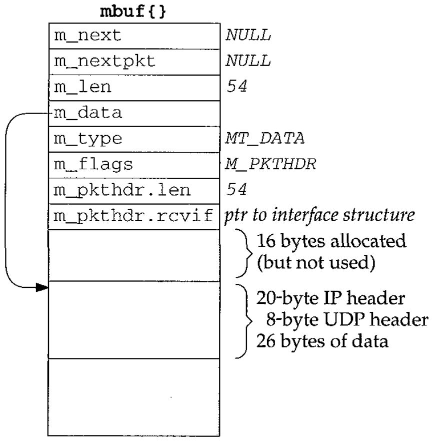


Figure 1.10 Single mbuf to hold input Ethernet data.

This mbuf is a packet header (the `M_PKTHDR` flag is set in `m_flags`) since it is the first mbuf of a data record. The `len` member in the packet header contains the total length of data and the `rcvif` member contains a pointer to the interface structure corresponding to the received interface (Chapter 3). We see that the `rcvif` member is used for received packets but not for output packets (Figures 1.7 and 1.8).

The first 16 bytes of the data portion of the mbuf are allocated for an interface layer header, but are not used. Since the amount of data (54 bytes) fits in the remaining 84 bytes of the mbuf, the data is stored in the mbuf itself.

The device driver passes the mbuf to a general Ethernet input routine which looks at the type field in the Ethernet frame to determine which protocol layer should receive the packet. In this example, the type field will specify an IP datagram, causing the mbuf to be added to the IP input queue. Additionally, a software interrupt is scheduled to cause the IP input process routine to be executed. The device's interrupt handling is then complete.

IP Input

IP input is asynchronous and is scheduled to run by a software interrupt. The software interrupt is set by the interface layer when it receives an IP datagram on one of the system's interfaces. When the IP input routine executes it loops, processing each IP datagram on its input queue and returning when the entire queue has been processed.

The IP input routine processes each IP datagram that it receives. It verifies the IP header checksum, processes any IP options, verifies that the datagram was delivered to the right host (by comparing the destination IP address of the datagram with the host's IP addresses), and forwards the datagram if the system was configured as a router and the datagram is destined for some other IP address. If the IP datagram has reached its final destination, the protocol field in the IP header specifies which protocol's input routine is called: ICMP, IGMP, TCP, or UDP. In our example, the UDP input routine is called to process the UDP datagram.

UDP Input

The UDP input routine verifies the fields in the UDP header (the length and optional checksum) and then determines whether or not a process should receive the datagram. In Chapter 23 we discuss exactly how this test is made. A process can receive all datagrams destined to a specified UDP port, or the process can tell the kernel to restrict the datagrams it receives based on the source and destination IP addresses and source and destination port numbers.

In our example, the UDP input routine starts at the global variable `udb` (Figure 1.5) and goes through the linked list of UDP protocol control blocks, looking for one with a local port number (`inp_lport`) that matches the destination port number of the received UDP datagram. This will be the PCB created by our call to `socket`, and the `inp_socket` member of this PCB points to the corresponding `socket` structure, allowing the received data to be queued for the correct socket.

> In our example program we never specify the local port number for our application. We'll see in Exercise 23.3 that a side effect of writing the first UDP datagram to a socket that has not yet bound a local port number is the automatic assignment by the kernel of a local port number (termed an *ephemeral port*) to that socket. That's how the `inp_lport` member of the PCB for our socket gets set to some nonzero value.

Since this UDP datagram is to be delivered to our process, the sender's IP address and UDP port number are placed into an mbuf, and this mbuf and the data (26 bytes in our example) are appended to the receive queue for the socket. Figure 1.11 shows the two mbufs that are appended to the socket's receive queue.

Comparing the second mbuf on this chain (the one of type `MT_DATA`) with the mbuf in Figure 1.10, the `m_len` and `m_pkthdr.len` members have both been decremented by 28 (20 bytes for the IP header and 8 for the UDP header) and the `m_data` pointer has been incremented by 28. This effectively removes the IP and UDP headers, leaving only the 26 bytes of data to be appended to the socket's receive queue.

The first mbuf in the chain contains a 16-byte Internet socket address structure with the sender's IP address and UDP port number. Its type is `MT_SONAME`, similar to the mbuf in Figure 1.6. This mbuf is created by the socket layer to return this information to the calling process through the `recvfrom` or `recvmsg` system calls. Even though there is room (16 bytes) in the second mbuf on this chain for this socket address structure, it must be stored in its own mbuf since it has a different type (`MT_SONAME` versus `MT_DATA`).

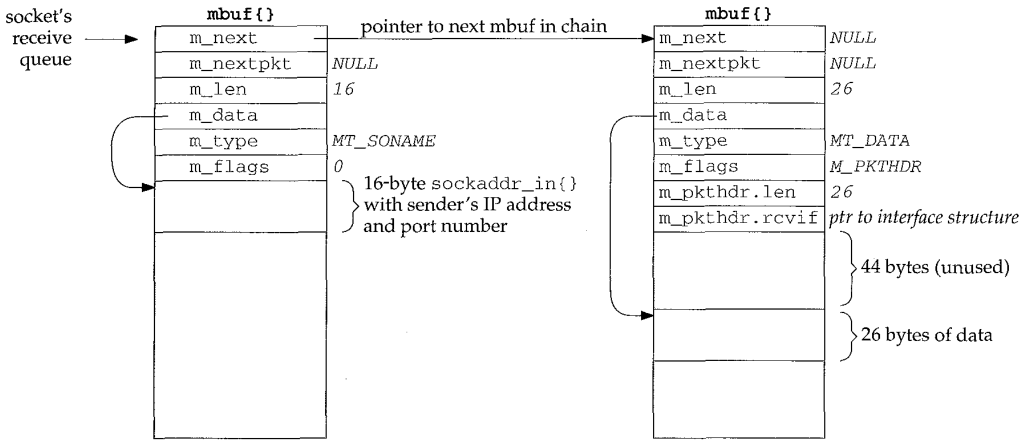


Figure 1.11 Sender's address and data.

The receiving process is then awakened. If the process is asleep waiting for data to arrive (which is the scenario in our example), the process is marked as run-able for the kernel to schedule. A process can also be notified of the arrival of data on a socket by the `select` system call or with the `SIGIO` signal.

Process Input

Our process has been asleep in the kernel, blocked in its call to `recvfrom`, and the process now wakes up. The 26 bytes of data appended to the socket's receive queue by the UDP layer (the received datagram) are copied by the kernel from the mbuf into our program's buffer.

Notice that our program sets the fifth and sixth arguments to `recvfrom` to null pointers, telling the system call that we're not interested in receiving the sender's IP address and UDP port number. This causes the `recvfrom` system call to skip the first mbuf in the chain (Figure 1.11), returning only the 26 bytes of data in the second mbuf. The kernel's `recvfrom` code then releases the two mbufs in Figure 1.11 and returns them to its pool of free mbufs.

1.11 Network Implementation Overview Revisited

Figure 1.12 summarizes the communication that takes place between the layers for both network output and network input. It repeats Figure 1.3 considering only the Internet protocols and emphasizing the communications between the layers.

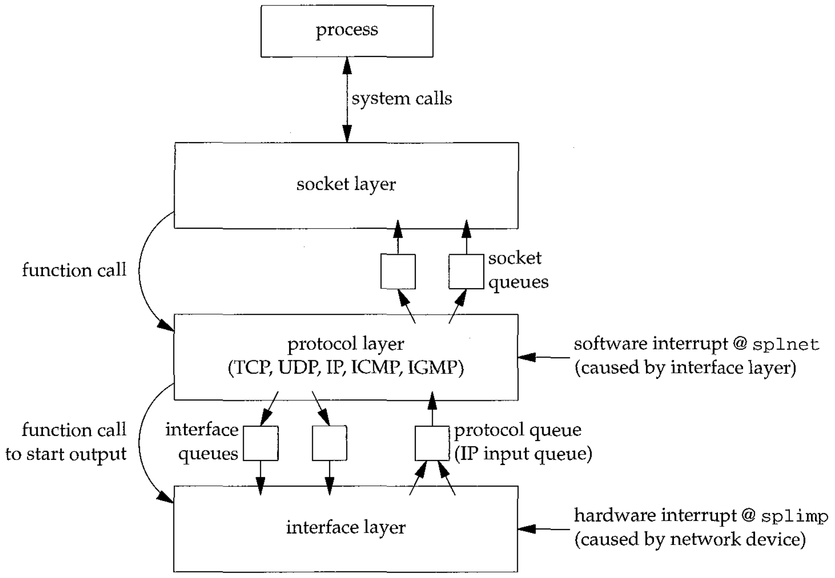

process
system calls
socket layer
function call
socket queues
protocol layer (TCP, UDP, IP, ICMP, IGMP)
software interrupt @ splnet (caused by interface layer)
function call to start output
interface queues
protocol queue (IP input queue)
interface layer
hardware interrupt @ splimp (caused by network device)

Figure 1.12 Communication between the layers for network input and output.

The notations `splnet` and `splimp` are discussed in the next section.

We use the plural terms *socket queues* and *interface queues* since there is one queue per socket and one queue per interface (Ethernet, loopback, SLIP, PPP, etc.), but we use the singular term *protocol queue* because there is a single IP input queue. If we considered other protocol layers, we would have one input queue for the XNS protocols and one for the OSI protocols.

1.12 Interrupt Levels and Concurrency

We saw in Section 1.10 that the processing of input packets by the networking code is asynchronous and interrupt driven. First, a device interrupt causes the interface layer code to execute, which posts a software interrupt that later causes the protocol layer code to execute. When the kernel is finished with these interrupt levels the socket code will execute.

There is a priority level assigned to each hardware and software interrupt. Figure 1.13 shows the normal ordering of the eight priority levels, from the lowest (no interrupts blocked) to the highest (all interrupts blocked).

Function	Description	
spl0	normal operating mode, nothing blocked	(lowest priority)
splsoftclock	low-priority clock processing	
splnet	network protocol processing	
spltty	terminal I/O	
splbio	disk and tape I/O	
splimp	network device I/O	
splclock	high-priority clock processing	
splhigh	all interrupts blocked	(highest priority)
splx(s)	(see text)	

Figure 1.13 Kernel functions that block selected interrupts.

Table 4.5 of [Leffler et al. 1989] shows the priority levels used in the VAX implementation. The Net/3 implementation for the 386 uses the eight functions shown in Figure 1.13, but `splsoftclock` and `splnet` are at the same level, and `splclock` and `splhigh` are also at the same level.

The name *imp* that is used for the network interface level comes from the acronym IMP (Interface Message Processor), which was the original type of router used on the ARPANET.

The ordering of the different priority levels means that a higher-priority interrupt can preempt a lower-priority interrupt. Consider the sequence of events depicted in Figure 1.14.

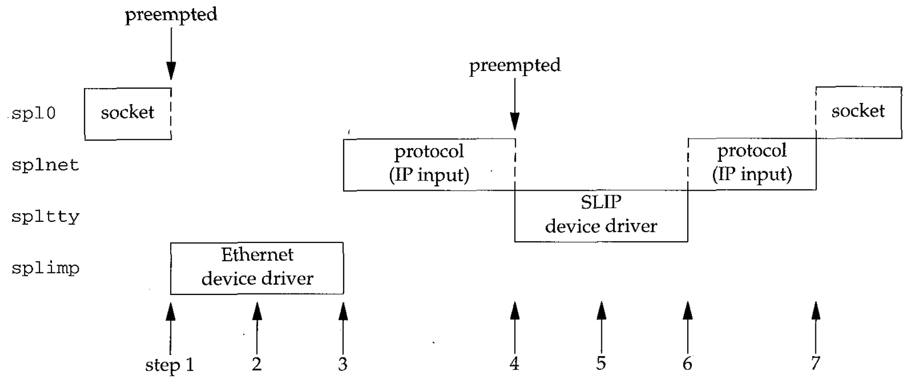


Figure 1.14 Example of priority levels and kernel processing.

1. While the socket layer is executing at `spl0`, an Ethernet device driver interrupt occurs, causing the interface layer to execute at `splimp`. This interrupt preempts the socket layer code. This is the asynchronous execution of the interface input routine.
2. While the Ethernet device driver is running, it places a received packet onto the IP input queue and schedules a software interrupt to occur at `splnet`. The

software interrupt won't take effect immediately since the kernel is currently running at a higher priority level (`splimp`).

3. When the Ethernet device driver completes, the protocol layer executes at `splnet`. This is the asynchronous execution of the IP input routine.
4. A terminal device interrupt occurs (say the completion of a SLIP packet) and it is handled immediately, preempting the protocol layer, since terminal I/O (`spltty`) is a higher priority than the protocol layer (`splnet`) in Figure 1.13. This is the asynchronous execution of the interface input routine.
5. The SLIP driver places the received packet onto the IP input queue and schedules another software interrupt for the protocol layer.
6. When the SLIP driver completes, the preempted protocol layer continues at `splnet`, finishes processing the packet received from the Ethernet device driver, and then processes the packet received from the SLIP driver. Only when there are no more input packets to process will it return control to whatever it preempted (the socket layer in this example).
7. The socket layer continues from where it was preempted.

One concern with these different priority levels is how to handle data structures shared between the different levels. Examples of shared data structures are the three we show between the different levels in Figure 1.12—the socket, interface, and protocol queues. For example, while the IP input routine is taking a received packet off its input queue, a device interrupt can occur, preempting the protocol layer, and that device driver can add another packet to the IP input queue. These shared data structures (the IP input queue in this example, which is shared between the protocol layer and the interface layer) can be corrupted if nothing is done to coordinate the shared access.

The Net/3 code is sprinkled with calls to the functions `splimp` and `splnet`. These two calls are always paired with a call to `splx` to return the processor to the previous level. For example, here is the code executed by the IP input function at the protocol layer to check if there is another packet on its input queue to process:

```
struct mbuf  *m;
int  s;

s = splimp();
IF_DEQUEUE(&ipintrq, m);
splx(s);

if (m == 0)
    return;
```

The call to `splimp` raises the CPU priority to the level used by the network device drivers, preventing any network device driver interrupt from occurring. The previous priority level is returned as the value of the function and stored in the variable `s`. Then the macro `IF_DEQUEUE` is executed to remove the next packet at the head of the IP input queue (`ipintrq`), placing the pointer to this mbuf chain in the variable `m`. Finally the CPU priority is returned to whatever it was when `splimp` was called, by calling `splx` with an argument of `s` (the saved value from the earlier call to `splimp`).

Since all network device driver interrupts are disabled between the calls to `splimp` and `splx`, the amount of code between these calls should be minimal. If interrupts are disabled for an extended period of time, additional device interrupts could be ignored, and data might be lost. For this reason the test of the variable `m` (to see if there is another packet to process) is performed after the call to `splx`, and not before the call.

The Ethernet output routine needs these `spl` calls when it places an outgoing packet onto an interface's queue, tests whether the interface is currently busy, and starts the interface if it was not busy.

```
struct mbuf  *m;
int  s;

s = splimp();
/*
 * Queue message on interface, and start output if interface not active.
 */
if (IF_QFULL(&ifp->if_snd)) {
    IF_DROP(&ifp->if_snd);     /* queue is full, drop packet */
    splx(s);
    error = ENOBUFS;
    goto bad;
}
IF_ENQUEUE(&ifp->if_snd, m);  /* add the packet to interface queue */
if ((ifp->if_flags & IFF_OACTIVE) == 0)
    (*ifp->if_start)(ifp);     /* start interface */
splx(s);
```

The reason device interrupts are disabled in this example is to prevent the device driver from taking the next packet off its send queue while the protocol layer is adding a packet to that queue. The driver's send queue is a data structure shared between the protocol layer and the interface layer.

We'll see calls to the `spl` functions throughout the source code.

1.13 Source Code Organization

Figure 1.15 shows the organization of the Net/3 networking source tree, assuming it is located in the `/usr/src/sys` directory.

This text focuses on the `netinet` directory, which contains all the TCP/IP source code. We also look at some files in the `kern` and `net` directories. The former contains the protocol-independent socket code, and the latter contains some general networking functions used by the TCP/IP routines, such as the routing code.

Briefly, the files contained in each directory are as follows:

- `i386`: the Intel 80x86-specific directories. For example, the directory `i386/isa` contains the device drivers specific to the ISA bus. The directory `i386/stand` contains the stand-alone bootstrap code.

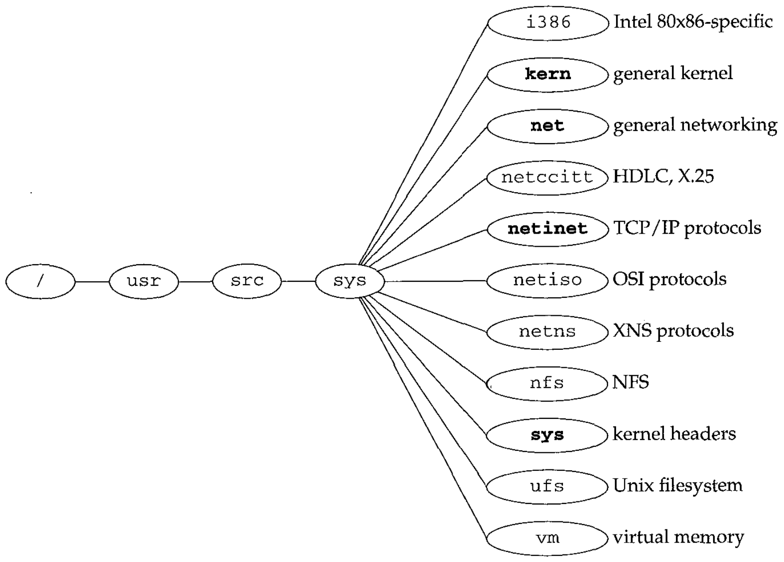


Figure 1.15 Net/3 source code organization.

- `kern`: general kernel files that don't belong in one of the other directories. For example, the kernel files to handle the `fork` and `exec` system calls are in this directory. We look at only a few files in this directory—the ones for the socket system calls (the socket layer in Figure 1.3).
- `net`: general networking files, for example, general network interface functions, the BPF (BSD Packet Filter) code, the SLIP driver, the loopback driver, and the routing code. We look at some of the files in this directory.
- `netccitt`: interface code for the OSI protocols, including the HDLC (high-level data-link control) and X.25 drivers.
- `netinet`: the code for the Internet protocols: IP, ICMP, IGMP, TCP, and UDP. This text focuses on the files in this directory.
- `netiso`: the OSI protocols.
- `netns`: the Xerox XNS protocols.
- `nfs`: code for Sun's Network File System.
- `sys`: system headers. We look at several headers in this directory. The files in this directory also appear in the directory `/usr/include/sys`.
- `ufs`: code for the Unix filesystem, sometimes called the *Berkeley fast filesystem*. This is the normal disk-based filesystem.
- `vm`: code for the virtual memory system.

Figure 1.16 gives another view of the source code organization, this time mapped to our three kernel layers. We ignore directories such as netimp and nfs that we don't consider in this text.

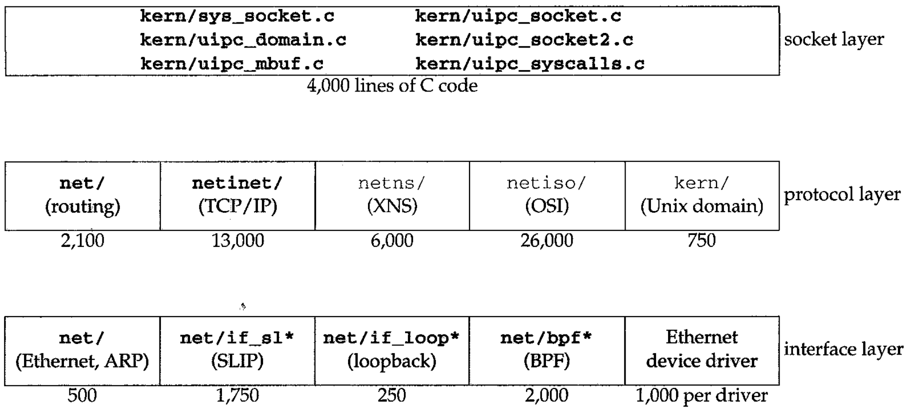


Figure 1.16 Net/3 source code organization mapped to three kernel layers.

The numbers below each box are the approximate number of lines of C code for that feature, which includes all comments in the source files.

We don't look at all the source code shown in this figure. The netns and netiso directories are shown for comparison against the Internet protocols. We only consider the shaded boxes.

1.14 Test Network

Figure 1.17 shows the test network that is used for all the examples in the text. Other than the host vangogh at the top of the figure, all the IP addresses belong to the class B network ID 140.252, and all the hostnames belong to the .tuc.noao.edu domain. (noao stands for "National Optical Astronomy Observatories" and tuc stands for Tucson.) For example, the system in the lower right has a complete hostname of svr4.tuc.noao.edu and an IP address of 140.252.13.34. The notation at the top of each box is the operating system running on that system.

The host at the top has a complete name of vangogh.cs.berkeley.edu and is reachable from the other hosts across the Internet.

This figure is nearly identical to the test network used in Volume 1, although some of the operating systems have been upgraded and the dialup link between sun and netb now uses PPP instead of SLIP. Additionally, we have replaced the Net/2 networking code provided with BSD/386 V1.1 with the Net/3 networking code.

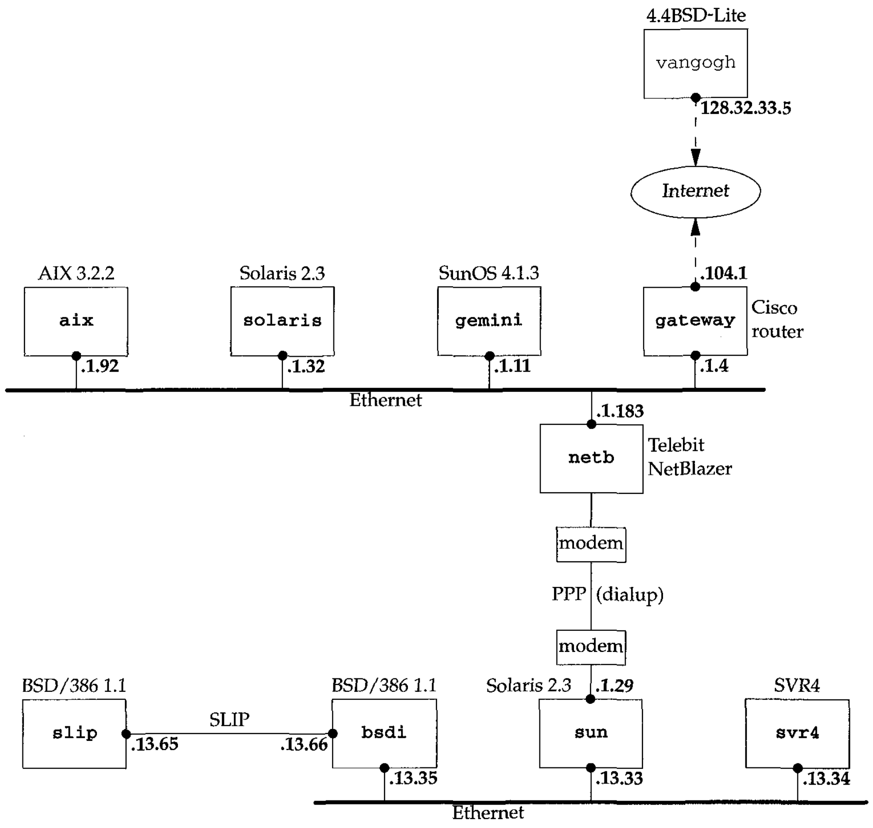


Figure 1.17 Test network used for all the examples in the text.

1.15 Summary

This chapter provided an overview of the Net/3 networking code. Using a simple program (Figure 1.2) that sends a UDP datagram to a daytime server and receives a reply, we've followed the resulting output and input through the kernel. Mbufs hold the information being output and the received IP datagrams. The next chapter examines mbufs in more detail.

UDP output occurs when the process executes the `sendto` system call, while IP input is asynchronous. When an IP datagram is received by a device driver, the datagram is placed onto IP's input queue and a software interrupt is scheduled to cause the IP input function to execute. We reviewed the different interrupt levels used by the networking code within the kernel. Since many of the networking data structures are shared by different layers that can execute at different interrupt priorities, the code must be careful when accessing or modifying these shared structures. We'll encounter calls to the `spl` functions in almost every function that we look at.

The chapter finishes with a look at the overall organization of the source code in Net/3, focusing on the code that this text examines.

Exercises

1.1 Type in the example program (Figure 1.2) and run it on your system. If your system has a system call tracing capability, such as `trace` (SunOS 4.x), `truss` (SVR4), or `ktrace` (4.4BSD), use it to determine the system calls invoked by this example.

1.2 In our example that calls `IF_DEQUEUE` in Section 1.12, we noted that the call to `splimp` blocks network device drivers from interrupting. While Ethernet drivers execute at this level, what happens to SLIP drivers?

2

Mbufs: Memory Buffers

2.1 Introduction

Networking protocols place many demands on the memory management facilities of the kernel. These demands include easily manipulating buffers of varying sizes, prepending and appending data to the buffers as the lower layers encapsulate data from higher layers, removing data from buffers (as headers are removed as data packets are passed up the protocol stack), and minimizing the amount of data copied for all these operations. The performance of the networking protocols is directly related to the memory management scheme used within the kernel.

In Chapter 1 we introduced the memory buffer used throughout the Net/3 kernel: the *mbuf*, which is an abbreviation for "memory buffer." In this chapter we look in more detail at mbufs and at the functions within the kernel that are used to manipulate them, as we will encounter mbufs on almost every page of the text. Understanding mbufs is essential for understanding the rest of the text.

The main use of mbufs is to hold the user data that travels from the process to the network interface, and vice versa. But mbufs are also used to contain a variety of other miscellaneous data: source and destination addresses, socket options, and so on.

Figure 2.1 shows the four different kinds of mbufs that we'll encounter, depending on the `M_PKTHDR` and `M_EXT` flags in the `m_flags` member. The differences between the four mbufs in Figure 2.1, from left to right, are as follows:

1. If `m_flags` equals 0, the mbuf contains only data. There is room in the mbuf for up to 108 bytes of data (the `m_dat` array). The `m_data` pointer points somewhere in this 108-byte buffer. We show it pointing to the start of the buffer, but it can point anywhere in the buffer. The `m_len` member specifies the number of bytes of data, starting at `m_data`. Figure 1.6 was an example of this type of mbuf.

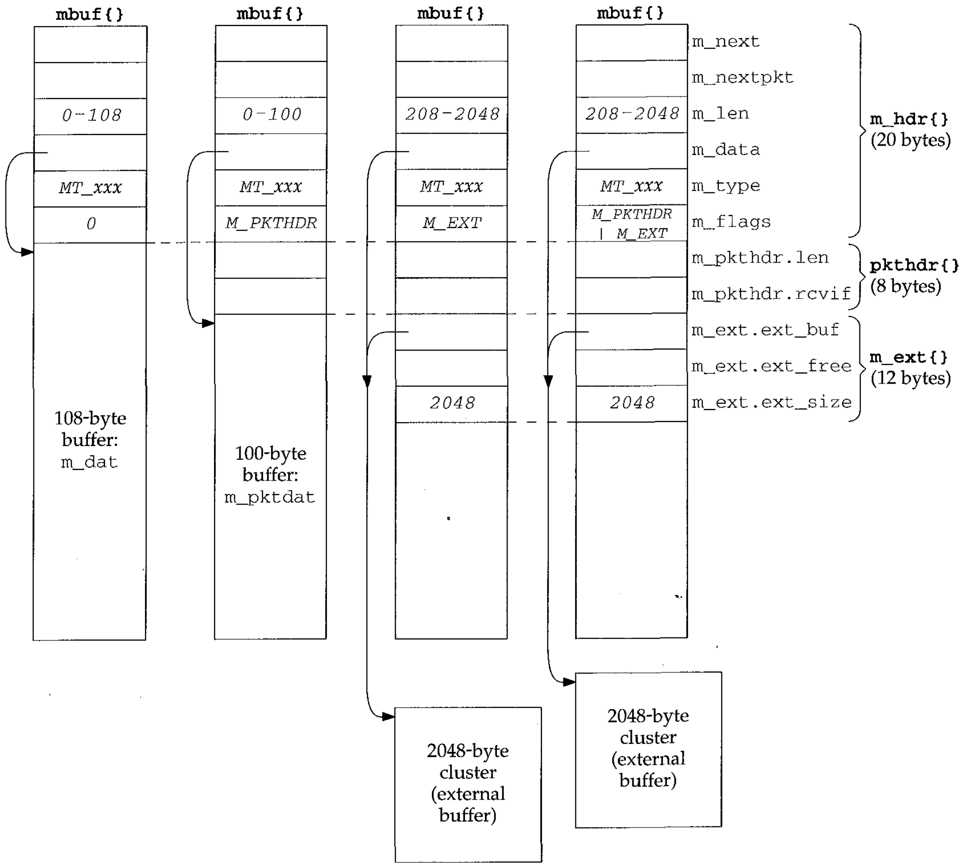


Figure 2.1 Four different types of mbufs, depending on the `m_flags` value.

In Figure 2.1 there are six members in the `m_hdr` structure, and its total size is 20 bytes. When we look at the C definition of this structure (Figure 2.8) we'll see that the first four members occupy 4 bytes each and the last two occupy 2 bytes each. We don't try to differentiate between the 4-byte members and the 2-byte members in Figure 2.1.

2. The second type of mbuf has an `m_flags` value of `M_PKTHDR`, specifying a *packet header*, that is, the first mbuf describing a packet of data. The data is still contained within the mbuf itself, but because of the 8 bytes taken by the packet header, only 100 bytes of data fit within this mbuf (in the `m_pktdat` array). Figure 1.10 was an example of this type of mbuf.

   The `m_pkthdr.len` value is the total length of all the data in the chain mbufs for this packet: the sum of the `m_len` values for all the mbufs linked through the m_next pointer, as shown in Figure 1.8. The m_pkthdr.rcvif member is not used for output packets, but for received packets contains a pointer to the received interface's ifnet structure (Figure 3.6).

3. The next type of mbuf does not contain a packet header (M_PKTHDR is not set) but contains more than 208 bytes of data, so an external buffer called a *cluster* is used (M_EXT is set). Room is still allocated in the mbuf itself for the packet header structure, but it is unused—we show it shaded in Figure 2.1. Instead of using multiple mbufs to contain the data (the first with 100 bytes of data, and all the rest with 108 bytes of data each), Net/3 allocates a cluster of size 1024 or 2048 bytes. The m_data pointer in the mbuf points somewhere inside this cluster.

   The Net/3 release supports seven different architectures. Four define the size of a cluster as 1024 bytes (the traditional value) and three define it as 2048. The reason 1024 has been used historically is to save memory: if the cluster size is 2048, about one-quarter of each cluster is unused for Ethernet packets (1500 bytes maximum). We'll see in Section 27.5 that the Net/3 TCP never sends more than the cluster size per TCP segment, so with a cluster size of 1024, almost one-third of each 1500-byte Ethernet frame is unused. But [Mogul 1993, Figure 15.15] shows that a sizable performance improvement occurs on an Ethernet when maximum-sized frames are sent instead of 1024-byte frames. This is a performance-versus-memory tradeoff. Older systems used 1024-byte clusters to save memory while newer systems with cheaper memory use 2048 to increase performance. Throughout this text we assume a cluster size of 2048.

   Unfortunately different names have been used for what we call *clusters*. The constant MCLBYTES is the size of these buffers (1024 or 2048) and the names of the macros to manipulate these buffers are MCLGET, MCLALLOC, and MCLFREE. This is why we call them *clusters*. But we also see that the mbuf flag is M_EXT, which stands for "external" buffer. Finally, [Leffler et al. 1989] calls them *mapped pages*. This latter name refers to their implementation, and we'll see in Section 2.9 that clusters can be shared when a copy is required.

   We would expect the minimum value of m_len to be 209 for this type of mbuf, not 208 as we indicate in the figure. That is, a record with 208 bytes of data can be stored in two mbufs, with 100 bytes in the first and 108 in the second. The source code, however, has a bug and allocates a cluster if the size is greater than or equal to 208.

4. The final type of mbuf contains a packet header and contains more than 208 bytes of data. Both M_PKTHDR and M_EXT are set.

There are numerous additional points we need to make about Figure 2.1:

- The size of the mbuf structure is always 128 bytes. This means the amount of unused space following the m_ext structure in the two mbufs on the right in Figure 2.1 is 88 bytes (128 – 20 – 8 – 12).
- A data buffer with an m_len of 0 bytes is OK since some protocols (e.g., UDP) allow 0-length records.

- In each of the mbufs we show the m_data member pointing to the beginning of the corresponding buffer (either the mbuf buffer itself or a cluster). This pointer can point anywhere in the corresponding buffer, not necessarily the front.
- Mbufs with a cluster always contain the starting address of the buffer (m_ext.ext_buf) and its size (m_ext.ext_size). We assume a size of 2048 throughout this text. The m_data and m_ext.ext_buf members are not the same (as we show) unless m_data also points to the first byte of the buffer. The third member of the m_ext structure, ext_free, is not currently used by Net/3.
- The m_next pointer links together the mbufs forming a single packet (record) into an *mbuf chain*, as in Figure 1.8.
- The m_nextpkt pointer links multiple packets (records) together to form a *queue of mbufs*. Each packet on the queue can be a single mbuf or an mbuf chain. The first mbuf of each packet contains a packet header. If multiple mbufs define a packet, the m_nextpkt member of the first mbuf is the only one used—the m_nextpkt member of the remaining mbufs on the chain are all null pointers.

Figure 2.2 shows an example of two packets on a queue. It is a modification of Figure 1.8. We have placed the UDP datagram onto the interface output queue (showing that the 14-byte Ethernet header has been prepended to the IP header in the first mbuf on the chain) and have added a second packet to the queue: a TCP segment containing 1460 bytes of user data. The TCP data is contained in a cluster and an mbuf has been prepended to contain its Ethernet, IP, and TCP headers. With the cluster we show that the data pointer into the cluster (m_data) need not point to the front of the cluster. We show that the queue has a head pointer and a tail pointer. This is how the interface output queues are handled in Net/3. We have also added the m_ext structure to the mbuf with the M_EXT flag set and have shaded in the unused pkthdr structure of this mbuf.

The first mbuf with the packet header for the UDP datagram has a type of MT_DATA, but the first mbuf with the packet header for the TCP segment has a type of MT_HEADER. This is a side effect of the different way UDP and TCP prepend the headers to their data, and makes no difference. Mbufs of these two types are essentially the same. It is the m_flags value of M_PKTHDR in the first mbuf on the chain that indicates a packet header.

Careful readers may note a difference between our picture of an mbuf (the Net/3 mbuf, Figure 2.1) and the picture in [Leffler et al. 1989, p. 290], a Net/1 mbuf. The changes were made in Net/2: adding the m_flags member, renaming the m_act pointer to be m_nextpkt, and moving this pointer to the front of the mbuf.

The difference in the placement of the protocol headers in the first mbuf for the UDP and TCP examples is caused by UDP calling M_PREPEND (Figure 23.15 and Exercise 23.1) while TCP calls MGETHDR (Figure 26.25).

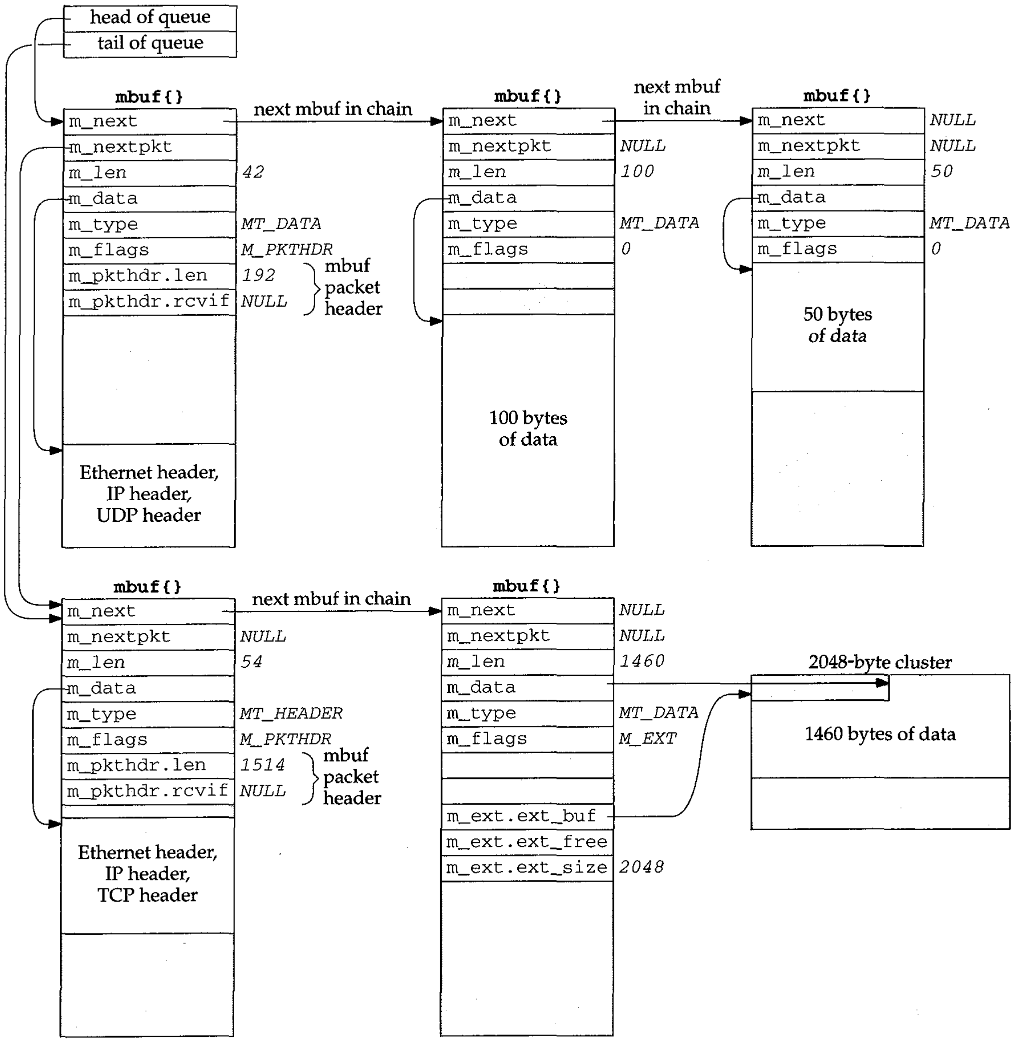


Figure 2.2 Two packets on a queue: first with 192 bytes of data and second with 1514 bytes of data.

2.2 Code Introduction

The mbuf functions are in a single C file and the mbuf macros and various mbuf definitions are in a single header, as shown in Figure 2.3.

File	Description
`sys/mbuf.h`	`mbuf` structure, mbuf macros and definitions
`kern/uipc_mbuf.c`	mbuf functions

Figure 2.3 Files discussed in this chapter.

Global Variables

One global variable is introduced in this chapter, shown in Figure 2.4.

Variable	Datatype	Description
`mbstat`	`struct mbstat`	mbuf statistics (Figure 2.5)

Figure 2.4 Global variables introduced in this chapter.

Statistics

Various statistics are maintained in the global structure `mbstat`, described in Figure 2.5.

`mbstat` member	Description
`m_clfree`	#free clusters
`m_clusters`	#clusters obtained from page pool
`m_drain`	#times protocol's drain functions called to reclaim space
`m_drops`	#times failed to find space (not used)
`m_mbufs`	#mbufs obtained from page pool (not used)
`m_mtypes[256]`	counter of current mbuf allocations: `MT_`*xxx* index
`m_spare`	spare field (not used)
`m_wait`	#times waited for space (not used)

Figure 2.5 Mbuf statistics maintained in the `mbstat` structure.

This structure can be examined with the `netstat -m` command; Figure 2.6 shows some sample output. The two values printed for the number of mapped pages in use are `m_clusters` (34) minus `m_clfree` (32), giving the number of clusters currently in use (2), and `m_clusters` (34).

The number of Kbytes of memory allocated to the network is the mbuf memory (99×128 bytes) plus the cluster memory (34×2048 bytes) divided by 1024. The percentage in use is the mbuf memory (99×128 bytes) plus the cluster memory in use (2×2048 bytes) divided by the total network memory (80 Kbytes), times 100.

netstat -m output	mbstat member
99 mbufs in use:	
1 mbufs allocated to data	m_mtypes[MT_DATA]
43 mbufs allocated to packet headers	m_mtypes[MT_HEADER]
17 mbufs allocated to protocol control blocks	m_mtypes[MT_PCB]
20 mbufs allocated to socket names and addresses	m_mtypes[MT_SONAME]
18 mbufs allocated to socket options	m_mtypes[MT_SOOPTS]
2/34 mapped pages in use	(see text)
80 Kbytes allocated to network (20% in use)	(see text)
0 requests for memory denied	m_drops
0 requests for memory delayed	m_wait
0 calls to protocol drain routines	m_drain

Figure 2.6 Sample mbuf statistics.

Kernel Statistics

The mbuf statistics show a common technique that we see throughout the Net/3 sources. The kernel keeps track of certain statistics in a global variable (the mbstat structure in this example). A process (in this case the netstat program) examines the statistics while the kernel is running.

Rather than provide system calls to fetch the statistics maintained by the kernel, the process obtains the address within the kernel of the data structure in which it is interested by reading the information saved by the link editor when the kernel was built. The process then calls the kvm(3) functions to read the corresponding location in the kernel's memory by using the special file /dev/mem. If the kernel's data structure changes from one release to the next, any program that reads that structure must also change.

2.3 Mbuf Definitions

There are a few constants that we encounter repeatedly when dealing with mbufs. Their values are shown in Figure 2.7. All are defined in mbuf.h except MCLBYTES, which is defined in /usr/include/machine/param.h.

Constant	Value (#bytes)	Description
MCLBYTES	2048	size of an mbuf cluster (external buffer)
MHLEN	100	max amount of data in mbuf with packet header
MINCLSIZE	208	smallest amount of data to put into cluster
MLEN	108	max amount of data in normal mbuf
MSIZE	128	size of each mbuf

Figure 2.7 Mbuf constants from mbuf.h.

2.4 mbuf Structure

Figure 2.8 shows the definition of the mbuf structure.

mbuf.h

```
/* header at beginning of each mbuf: */
struct m_hdr {
    struct mbuf *mh_next;       /* next buffer in chain */
    struct mbuf *mh_nextpkt;    /* next chain in queue/record */
    int     mh_len;             /* amount of data in this mbuf */
    caddr_t mh_data;            /* pointer to data */
    short   mh_type;            /* type of data (Figure 2.10) */
    short   mh_flags;           /* flags (Figure 2.9) */
};

/* record/packet header in first mbuf of chain; valid if M_PKTHDR set */
struct pkthdr {
    int     len;                /* total packet length */
    struct ifnet *rcvif;        /* receive interface */
};

/* description of external storage mapped into mbuf, valid if M_EXT set */
struct m_ext {
    caddr_t ext_buf;            /* start of buffer */
    void    (*ext_free) ();     /* free routine if not the usual */
    u_int   ext_size;           /* size of buffer, for ext_free */
};

struct mbuf {
    struct m_hdr m_hdr;
    union {
        struct {
            struct pkthdr MH_pkthdr;    /* M_PKTHDR set */
            union {
                struct m_ext MH_ext;    /* M_EXT set */
                char    MH_databuf[MHLEN];
            } MH_dat;
        } MH;
        char    M_databuf[MLEN];    /* !M_PKTHDR, !M_EXT */
    } M_dat;
};

#define m_next      m_hdr.mh_next
#define m_len       m_hdr.mh_len
#define m_data      m_hdr.mh_data
#define m_type      m_hdr.mh_type
#define m_flags     m_hdr.mh_flags
#define m_nextpkt   m_hdr.mh_nextpkt
#define m_act       m_nextpkt
#define m_pkthdr    M_dat.MH.MH_pkthdr
#define m_ext       M_dat.MH.MH_dat.MH_ext
#define m_pktdat    M_dat.MH.MH_dat.MH_databuf
#define m_dat       M_dat.M_databuf
```

mbuf.h

Figure 2.8 Mbuf structures.

The mbuf structure is defined as an m_hdr structure, followed by a union. As the comments indicate, the contents of the union depend on the flags M_PKTHDR and M_EXT.

93-103 These 11 #define statements simplify access to the members of the structures and unions within the mbuf structure. We will see this technique used throughout the Net/3 sources whenever we encounter a structure containing other structures or unions.

We previously described the purpose of the first two members in the mbuf structure: the m_next pointer links mbufs together into an mbuf chain and the m_nextpkt pointer links mbuf chains together into a *queue of mbufs*.

Figure 1.8 differentiated between the m_len member of each mbuf and the m_pkthdr.len member in the packet header. The latter is the sum of all the m_len members of all the mbufs on the chain.

There are five independent values for the m_flags member, shown in Figure 2.9.

m_flags	Description
M_BCAST	sent/received as link-level broadcast
M_EOR	end of record
M_EXT	cluster (external buffer) associated with this mbuf
M_MCAST	sent/received as link-level multicast
M_PKTHDR	first mbuf that forms a packet (record)
M_COPYFLAGS	*M_PKTHDR | M_EOR | M_BCAST | M_MCAST*

Figure 2.9 m_flags values.

We have already described the M_EXT and M_PKTHDR flags. M_EOR is set in an mbuf containing the end of a record. The Internet protocols (e.g., TCP) never set this flag, since TCP provides a byte-stream service without any record boundaries. The OSI and XNS transport layers, however, do use this flag. We will encounter this flag in the socket layer, since this layer is protocol independent and handles data to and from all the transport layers.

The next two flags, M_BCAST and M_MCAST, are set in an mbuf when the packet will be sent to or was received from a link-layer broadcast address or multicast address. These two constants are flags between the protocol layer and the interface layer (Figure 1.3).

The final value, M_COPYFLAGS, specifies the flags that are copied when an mbuf containing a packet header is copied.

Figure 2.10 shows the MT_*xxx* constants used in the m_type member to identify the type of data stored in the mbuf. Although we tend to think of an mbuf as containing user data that is sent or received, mbufs can contain a variety of different data structures. Recall in Figure 1.6 that an mbuf was used to hold a socket address structure with the destination address for the sendto system call. Its m_type member was set to MT_SONAME.

Not all of the mbuf type values in Figure 2.10 are used in Net/3. Some are historical (MT_HTABLE), and others are not used in the TCP/IP code but are used elsewhere in the

Mbuf m_type	Used in Net/3 TCP/IP code	Description	Memory type
MT_CONTROL	•	extra-data protocol message	M_MBUF
MT_DATA	•	dynamic data allocation	M_MBUF
MT_FREE		should be on free list	M_FREE
MT_FTABLE	•	fragment reassembly header	M_FTABLE
MT_HEADER	•	packet header	M_MBUF
MT_HTABLE		IMP host tables	M_HTABLE
MT_IFADDR		interface address	M_IFADDR
MT_OOBDATA		expedited (out-of-band) data	M_MBUF
MT_PCB		protocol control block	M_PCB
MT_RIGHTS		access rights	M_MBUF
MT_RTABLE		routing tables	M_RTABLE
MT_SONAME	•	socket name	M_MBUF
MT_SOOPTS	•	socket options	M_SOOPTS
MT_SOCKET		socket structure	M_SOCKET

Figure 2.10 Values for m_type member.

kernel. For example, MT_OOBDATA is used by the OSI and XNS protocols, but TCP handles out-of-band data differently (as we describe in Section 29.7). We describe the use of other mbuf types when we encounter them later in the text.

The final column of this figure shows the M_*xxx* values associated with the piece of memory allocated by the kernel for the different types of mbufs. There are about 60 possible M_*xxx* values assigned to the different types of memory allocated by the kernel's malloc function and MALLOC macro. Figure 2.6 showed the mbuf allocation statistics from the netstat -m command including the counters for each MT_*xxx* type. The vmstat -m command shows the kernel's memory allocation statistics including the counters for each M_*xxx* type.

Since mbufs have a fixed size (128 bytes) there is a limit for what an mbuf can be used for—the data contents cannot exceed 108 bytes. Net/2 used an mbuf to hold a TCP protocol control block (which we cover in Chapter 24), using the mbuf type of MT_PCB. But 4.4BSD increased the size of this structure from 108 bytes to 140 bytes, forcing the use of a different type of kernel memory allocation for the structure.

Observant readers may have noticed that in Figure 2.10 we say that mbufs of type MT_PCB are not used, yet Figure 2.6 shows a nonzero counter for this type. The Unix domain protocols use this type of mbuf, and it is important to remember that the statistics are for mbuf usage across all protocol suites, not just the Internet protocols.

2.5 Simple Mbuf Macros and Functions

There are more than two dozen macros and functions that deal with mbufs (allocate an mbuf, free an mbuf, etc.). We look at the source code for only a few of the macros and functions, to show how they're implemented.

Some operations are provided as both a macro and function. The macro version has an uppercase name that begins with `M`, and the function has a lowercase name that begins with `m_`. The difference in the two is the standard time-versus-space tradeoff. The macro version is expanded inline by the C preprocessor each time it is used (requiring more code space), but it executes faster since it doesn't require a function call (which can be expensive on some architectures). The function version, on the other hand, becomes a few instructions each time it is invoked (push the arguments onto the stack, call the function, etc.), taking less code space but more execution time.

`m_get` Function

We'll look first at the function that allocates an mbuf: `m_get`, shown in Figure 2.11. This function merely expands the macro `MGET`.

uipc_mbuf.c

```
struct mbuf *
m_get(nowait, type)
int     nowait, type;
{
    struct mbuf *m;

    MGET(m, nowait, type);
    return (m);
}
```

uipc_mbuf.c

Figure 2.11 `m_get` function: allocate an mbuf.

Notice that the Net/3 code does not use ANSI C argument declarations. All the Net/3 system headers, however, *do* provide ANSI C function prototypes for all kernel functions, if an ANSI C compiler is being used. For example, the `<sys/mbuf.h>` header includes the line

```
struct  mbuf *m_get(int, int);
```

These function prototypes provide compile-time checking of the arguments and return values whenever a kernel function is called.

The caller specifies the `nowait` argument as either `M_WAIT` or `M_DONTWAIT`, depending whether it wants to wait if the memory is not available. As an example of the difference, when the socket layer asks for an mbuf to store the destination address of the `sendto` system call (Figure 1.6) it specifies `M_WAIT`, since blocking at this point is OK. But when the Ethernet device driver asks for an mbuf to store a received frame (Figure 1.10) it specifies `M_DONTWAIT`, since it is executing as a device interrupt handler and cannot be put to sleep waiting for an mbuf. In this case it is better for the device driver to discard the Ethernet frame if the memory is not available.

`MGET` Macro

Figure 2.12 shows the `MGET` macro. A call to `MGET` to allocate the mbuf to hold the destination address for the `sendto` system call (Figure 1.6) might look like

```
MGET(m, M_WAIT, MT_SONAME);
if (m == NULL)
    return(ENOBUFS);
```

Even though the caller specifies `M_WAIT`, the return value must still be checked, since, as we'll see in Figure 2.13, waiting for an mbuf does not guarantee that one will be available.

mbuf.h

```
154 #define MGET(m, how, type) { \
155     MALLOC((m), struct mbuf *, MSIZE, mbtypes[type], (how)); \
156     if (m) { \
157         (m)->m_type = (type); \
158         MBUFLOCK(mbstat.m_mtypes[type]++;) \
159         (m)->m_next = (struct mbuf *)NULL; \
160         (m)->m_nextpkt = (struct mbuf *)NULL; \
161         (m)->m_data = (m)->m_dat; \
162         (m)->m_flags = 0; \
163     } else \
164         (m) = m_retry((how), (type)); \
165 }
```

mbuf.h

Figure 2.12 MGET macro.

154–157 `MGET` first calls the kernel's `MALLOC` macro, which is the general-purpose kernel memory allocator. The array `mbtypes` converts the mbuf `MT_`*xxx* value into the corresponding `M_`*xxx* value (Figure 2.10). If the memory can be allocated, the `m_type` member is set to the argument's value.

158 The kernel structure that keeps mbuf statistics for each type of mbuf is incremented (`mbstat`). The macro `MBUFLOCK` changes the processor priority (Figure 1.13) while executing the statement specified as its argument, and then resets the priority to its previous value. This prevents network device interrupts from occurring while the statement `mbstat.m_mtypes[type]++;` is executing, because mbufs can be allocated at various layers within the kernel. Consider a system that implements the ++ operator in C using three steps: (1) load the current value into a register, (2) increment the register, and (3) store the register into memory. Assume the counter's value is 77 and `MGET` is executing at the socket layer. Assume steps 1 and 2 are executed (the register's value is 78) and a device interrupt occurs. If the device driver also executes `MGET` for the same type of mbuf, the value in memory is fetched (77), incremented (78), and stored back into memory. When step 3 of the interrupted execution of `MGET` resumes, it stores its register (78) into memory. But the counter should be 79, not 78, so the counter has been corrupted.

159–160 The two mbuf pointers, `m_next` and `m_nextpkt`, are set to null pointers. It is the caller's responsibility to add the mbuf to a chain or queue, if necessary.

161–162 Finally the data pointer is set to point to the beginning of the 108-byte mbuf buffer and the flags are set to 0.

163–164 If the call to the kernel's memory allocator fails, `m_retry` is called (Figure 2.13). The first argument is either `M_WAIT` or `M_DONTWAIT`.

`m_retry` Function

Figure 2.13 shows the `m_retry` function.

uipc_mbuf.c

```
 92 struct mbuf *
 93 m_retry(i, t)
 94 int     i, t;
 95 {
 96     struct mbuf *m;

 97     m_reclaim();
 98 #define m_retry(i, t)    (struct mbuf *)0
 99     MGET(m, i, t);
100 #undef m_retry
101     return (m);
102 }
```

uipc_mbuf.c

Figure 2.13 `m_retry` function.

92–97 The first function called by `m_retry` is `m_reclaim`. We'll see in Section 7.4 that each protocol can define a "drain" function to be called by `m_reclaim` when the system gets low on available memory. We'll also see in Figure 10.32 that when IP's drain function is called, all IP fragments waiting to be reassembled into IP datagrams are discarded. TCP's drain function does nothing and UDP doesn't even define a drain function.

98–102 Since there's a chance that more memory *might* be available after the call to `m_reclaim`, the `MGET` macro is called again, to try to obtain the mbuf. Before expanding the `MGET` macro (Figure 2.12), `m_retry` is defined to be a null pointer. This prevents an infinite loop if the memory still isn't available: the expansion of `MGET` will set `m` to this null pointer instead of calling the `m_retry` function. After the expansion of `MGET`, this temporary definition of `m_retry` is undefined, in case there is another reference to `MGET` later in the source file.

Mbuf Locking

In the functions and macros that we've looked at in this section, other than the call to `MBUFLOCK` in Figure 2.12, there are no calls to the `spl` functions to protect these functions and macros from being interrupted. What we haven't shown, however, is that the macro `MALLOC` contains an `splimp` at the beginning and an `splx` at the end. The macro `MFREE` contains the same protection. Mbufs are allocated and released at all layers within the kernel, so the kernel must protect the data structures that it uses for memory allocation.

Additionally, the macros `MCLALLOC` and `MCLFREE`, which allocate and release an mbuf cluster, are surrounded by an `splimp` and an `splx`, since they modify a linked list of available clusters.

Since the memory allocation and release macros along with the cluster allocation and release macros are protected from interrupts, we normally do not encounter calls to the `spl` functions around macros and functions such as `MGET` and `m_get`.

2.6 m_devget and m_pullup Functions

We encounter the m_pullup function when we show the code for IP, ICMP, IGMP, UDP, and TCP. It is called to guarantee that the specified number of bytes (the size of the corresponding protocol header) are contiguous in the first mbuf of a chain; otherwise the specified number of bytes are copied to a new mbuf and made contiguous. To understand the usage of m_pullup we must describe its implementation and its interaction with both the m_devget function and the mtod and dtom macros. This description also provides additional insight into the usage of mbufs in Net/3.

m_devget Function

When an Ethernet frame is received, the device driver calls the function m_devget to create an mbuf chain and copy the frame from the device into the chain. Depending on the length of the received frame (excluding the Ethernet header), there are four different possibilities for the resulting mbuf chain. The first two possibilities are shown in Figure 2.14.

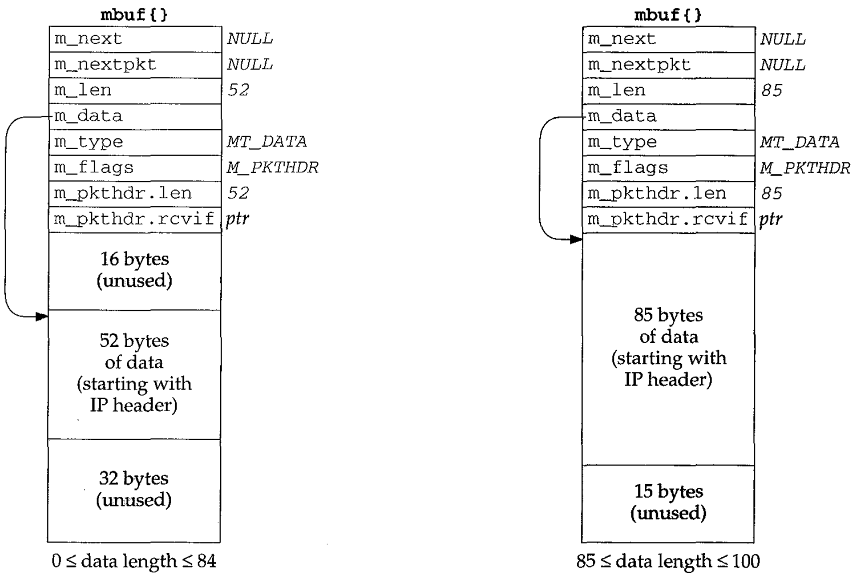


Figure 2.14 First two types of mbufs created by m_devget.

1. The left mbuf in Figure 2.14 is used when the amount of data is between 0 and 84 bytes. In this figure we assume there are 52 bytes of data: a 20-byte IP header and a 32-byte TCP header (the standard 20-byte TCP header plus 12 bytes of TCP options)

but no TCP data. Since the data in the mbuf returned by m_devget starts with the IP header, the realistic minimum value for m_len is 28: 20 bytes for an IP header, 8 bytes for a UDP header, and a 0-length UDP datagram.

m_devget leaves 16 bytes unused at the beginning of the mbuf. Although the 14-byte Ethernet header is not stored here, room is allocated for a 14-byte Ethernet header on output, should the same mbuf be used for output. We'll encounter two functions that generate a response by using the received mbuf as the outgoing mbuf: icmp_reflect and tcp_respond. In both cases the size of the received datagram is normally less than 84 bytes, so it costs nothing to leave room for 16 bytes at the front, which saves time when building the outgoing datagram. The reason 16 bytes are allocated, and not 14, is to have the IP header longword aligned in the mbuf.

2. If the amount of data is between 85 and 100 bytes, the data still fits in a packet header mbuf, but there is no room for the 16 bytes at the beginning. The data starts at the beginning of the m_pktdat array and any unused space is at the end of this array. The mbuf on the right in Figure 2.14 shows this example, assuming 85 bytes of data.

3. Figure 2.15 shows the third type of mbuf created by m_devget. Two mbufs are required when the amount of data is between 101 and 207 bytes. The first 100 bytes are stored in the first mbuf (the one with the packet header), and the remainder are stored in the second mbuf. In this example we show a 104-byte datagram. No attempt is made to leave 16 bytes at the beginning of the first mbuf.

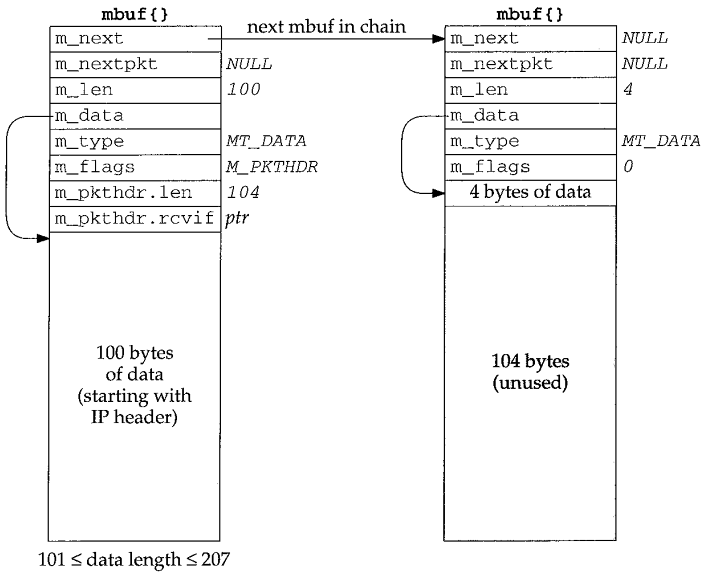


Figure 2.15 Third type of mbuf created by m_devget.

4. Figure 2.16 shows the fourth type of mbuf created by m_devget. If the amount of data is greater than or equal to 208 (MINCLBYTES), one or more clusters are used. The example in the figure assumes a 1500-byte Ethernet frame with 2048-byte clusters. If 1024-byte clusters are in use, this example would require two mbufs, each with the M_EXT flag set, and each pointing to a cluster.

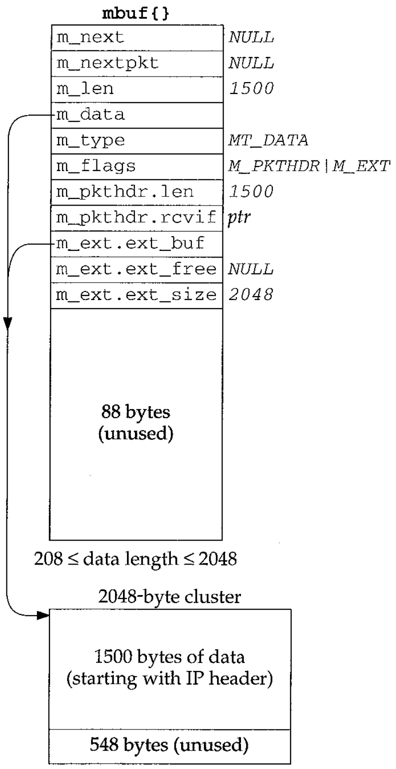


Figure 2.16 Fourth type of mbuf created by m_devget.

mtod and dtom Macros

The two macros mtod and dtom are also defined in mbuf.h. They simplify complex mbuf structure expressions.

```
#define  mtod(m,t)   ((t)((m)->m_data))
#define  dtom(x)     ((struct mbuf *)((int)(x) & ~(MSIZE-1)))
```

mtod ("mbuf-to-data") returns a pointer to the data associated with an mbuf, and casts the pointer to a specified type. For example, the code

```
struct mbuf *m;
struct ip *ip;

ip = mtod(m, struct ip *);
ip->ip_v = IPVERSION;
```

stores in ip the data pointer of the mbuf (m_data). The type cast is required by the C compiler and the code then references the IP header using the pointer ip. We see this macro used when a C structure (often a protocol header) is stored in an mbuf. This macro works if the data is stored in the mbuf itself (Figures 2.14 and 2.15) or if the data is stored in a cluster (Figure 2.16).

The macro dtom ("data-to-mbuf") takes a pointer to data anywhere within the data portion of the mbuf and returns a pointer to the mbuf structure itself. For example, if we know that ip points within the data area of an mbuf, the sequence

```
struct mbuf *m;
struct ip *ip;

m = dtom(ip);
```

stores the pointer to the beginning of the mbuf in m. By knowing that MSIZE (128) is a power of 2, and that mbufs are always aligned by the kernel's memory allocator on MSIZE byte blocks of memory, dtom just clears the appropriate low-order bits in its argument pointer to find the beginning of the mbuf.

There is a problem with dtom: it doesn't work if its argument points to a cluster, or within a cluster, as in Figure 2.16. Since there is no pointer from the cluster back to the mbuf structure, dtom cannot be used. This leads to the next function, m_pullup.

m_pullup Function and Contiguous Protocol Headers

The m_pullup function has two purposes. The first is when one of the protocols (IP, ICMP, IGMP, UDP, or TCP) finds that the amount of data in the first mbuf (m_len) is less than the size of the minimum protocol header (e.g., 20 for IP, 8 for UDP, 20 for TCP). m_pullup is called on the assumption that the remaining part of the header is in the next mbuf on the chain. m_pullup rearranges the mbuf chain so that the first *N* bytes of data are contiguous in the first mbuf on the chain. *N* is an argument to the function that must be less than or equal to 100 (MHLEN). If the first *N* bytes are contiguous in the first mbuf, then both of the macros mtod and dtom will work.

For example, we'll encounter the following code in the IP input routine:

```
if (m->m_len < sizeof(struct ip) &&
    (m = m_pullup(m, sizeof(struct ip))) == 0) {
        ipstat.ips_toosmall++;
        goto next;
}
ip = mtod(m, struct ip *);
```

If the amount of data in the first mbuf is less than 20 (the size of the standard IP header), m_pullup is called. m_pullup can fail for two reasons: (1) if it needs another mbuf and its call to MGET fails, or (2) if the total amount of data in the mbuf chain is less than the requested number of contiguous bytes (what we called *N*, which in this case is 20). The second reason is the most common cause of failure. In this example, if m_pullup fails, an IP counter is incremented and the IP datagram is discarded. Notice that this code assumes the reason for failure is that the amount of data in the mbuf chain is less than 20 bytes.

In actuality, m_pullup is rarely called in this scenario (notice that C's && operator only calls it when the mbuf length is smaller than expected) and when it is called, it normally fails. The reason can be seen by looking at Figure 2.14 through Figure 2.16: there is room in the first mbuf, or in the cluster, for at least 100 contiguous bytes, starting with the IP header. This allows for the maximum IP header of 60 bytes followed by 40 bytes of TCP header. (The other protocols—ICMP, IGMP, and UDP—have headers smaller than 40 bytes.) If the data bytes are available in the mbuf chain (the packet is not smaller than the minimum required by the protocol), then the required number of bytes should always be contiguous in the first mbuf. But if the received packet is too short (m_len is less than the expected minimum), then m_pullup is called and it returns an error, since the required amount of data is not available in the mbuf chain.

Berkeley-derived kernels maintain a variable named MPFail that is incremented each time m_pullup fails. On a Net/3 system that had received over 27 million IP datagrams, MPFail was 9. The counter ipstat.ips_toosmall was also 9 and all the other protocol counters (i.e., ICMP, IGMP, UDP, and TCP) following a failure of m_pullup were 0. This confirms our statement that most failures of m_pullup are because the received IP datagram was too small.

m_pullup and IP Fragmentation and Reassembly

The second use of m_pullup concerns IP reassembly and TCP reassembly. Assume IP receives a packet of length 296, which is a fragment of a larger IP datagram. The mbuf passed from the device driver to IP input looks like the one we showed in Figure 2.16: the 296 bytes of data are stored in a cluster. We show this in Figure 2.17.

The problem is that the IP fragmentation algorithm keeps the individual fragments on a doubly linked list, using the source and destination IP address fields in the IP header to hold the forward and backward list pointers. (These two IP addresses are saved, of course, in the head of the list, since they must be put back into the reassembled datagram. We describe this in Chapter 10.) But if the IP header is in a cluster, as shown in Figure 2.17, these linked list pointers would be in the cluster, and when the list is traversed at some later time, the pointer to the IP header (i.e., the pointer to the beginning of the cluster) could not be converted into the pointer to the mbuf. This is the problem we mentioned earlier in this section: the dtom macro cannot be used if m_data points into a cluster, because there is no back pointer from the cluster to the mbuf. IP fragmentation cannot store the links in the cluster as shown in Figure 2.17.

To solve this problem the IP fragmentation routine *always* calls m_pullup when a fragment is received, if the fragment is contained in a cluster. This forces the 20-byte IP header into its own mbuf. The code looks like

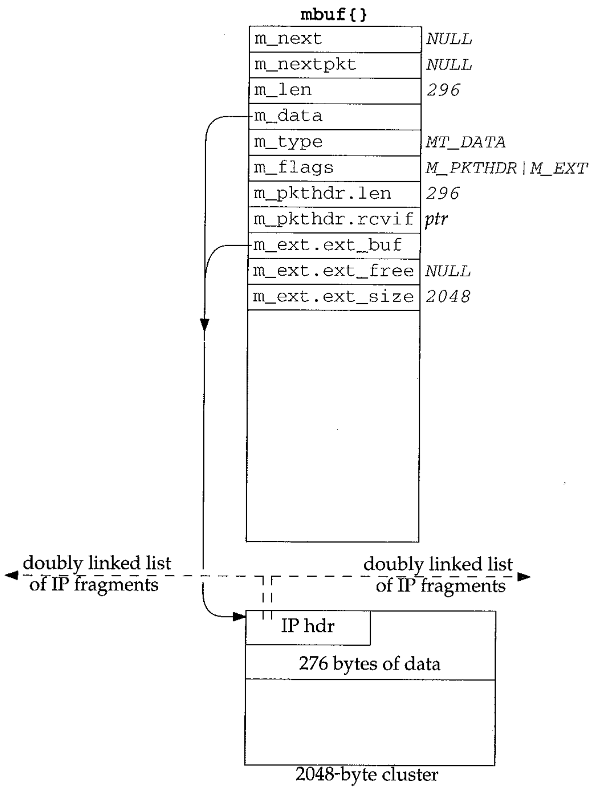


Figure 2.17 An IP fragment of length 296.

```
if (m->m_flags & M_EXT) {
    if ((m = m_pullup(m, sizeof(struct ip))) == 0) {
        ipstat.ips_toosmall++;
        goto next;
    }
    ip = mtod(m, struct ip *);
}
```

Figure 2.18 shows the resulting mbuf chain, after m_pullup is called. m_pullup allocates a new mbuf, prepends it to the chain, and moves the first 40 bytes of data from the cluster into the new mbuf. The reason it moves 40 bytes, and not just the requested 20, is to try to save an additional call at a later time when IP passes the datagram to a higher-layer protocol (e.g., ICMP, IGMP, UDP, or TCP). The magic number 40 (max_protohdr in Figure 7.17) is because the largest protocol header normally encountered is the combination of a 20-byte IP header and a 20-byte TCP header. (This

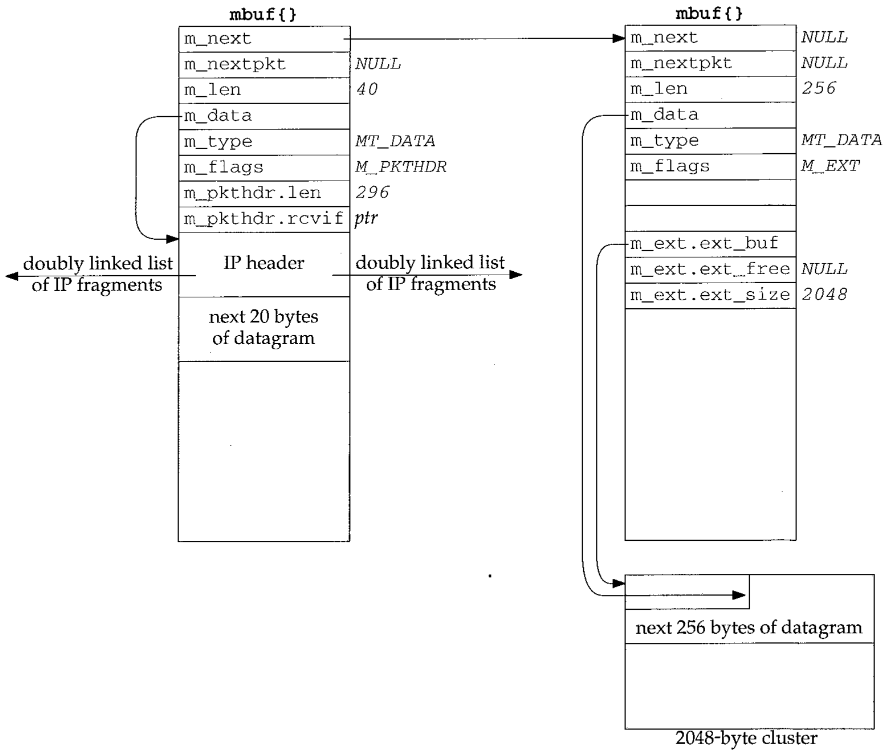


Figure 2.18 An IP fragment of length 296, after calling `m_pullup`.

assumes that other protocol suites, such as the OSI protocols, are not compiled into the kernel.)

In Figure 2.18 the IP fragmentation algorithm can save a pointer to the IP header contained in the mbuf on the left, and this pointer can be converted into a pointer to the mbuf itself using `dtom` at a later time.

Avoidance of `m_pullup` by TCP Reassembly

The reassembly of TCP segments uses a different technique to avoid calling `m_pullup`. This is because `m_pullup` is expensive: memory is allocated and data is copied from a cluster to an mbuf. TCP tries to avoid data copying whenever possible.

Chapter 19 of Volume 1 mentions that about one-half of TCP data is bulk data (often 512 or more bytes of data per segment) and the other half is interactive data (of which about 90% of the segments contain less than 10 bytes of data). Hence, when TCP receives segments from IP they are usually in the format shown on the left of Figure 2.14 (a small amount of interactive data, stored in the mbuf itself) or in the format shown in

Figure 2.16 (bulk data, stored in a cluster). When TCP segments arrive out of order, they are stored on a doubly linked list by TCP. As with IP fragmentation, fields in the IP header are used to hold the list pointers, which is OK since these fields are no longer needed once the IP datagram is accepted by TCP. But the same problem arises with the conversion of a list pointer into the corresponding mbuf pointer, when the IP header is stored in a cluster (Figure 2.17).

To solve the problem, we'll see in Section 27.9 that TCP stores the mbuf pointer in some unused fields in the TCP header, providing a back pointer of its own from the cluster to the mbuf, just to avoid calling `m_pullup` for every out-of-order segment. If the IP header is contained in the data portion of the mbuf (Figure 2.18), then this back pointer is superfluous, since the `dtom` macro would work on the list pointer. But if the IP header is contained in a cluster, this back pointer is required. We'll examine the source code that implements this technique when we describe `tcp_reass` in Section 27.9.

Summary of `m_pullup` Usage

We've described three main points about `m_pullup`.

- Most device drivers do not split the first portion of an IP datagram between mbufs. Therefore the possible calls to `m_pullup` that we'll encounter in every protocol (IP, ICMP, IGMP, UDP, and TCP), just to assure that the protocol header is stored contiguously, rarely take place. When these calls to `m_pullup` do occur, it is normally because the IP datagram is too small, in which case `m_pullup` returns an error, the datagram is discarded, and an error counter is incremented.
- `m_pullup` is called for every received IP fragment, when the IP fragment is stored in a cluster. This means that `m_pullup` is called for almost every received fragment, since the length of most fragments is greater than 208 bytes.
- As long as TCP segments are not fragmented by IP, the receipt of a TCP segment, whether it be in order or out of order, should not invoke `m_pullup`. This is one reason to avoid IP fragmentation with TCP.

2.7 Summary of Mbuf Macros and Functions

Figure 2.19 lists the macros and Figure 2.20 lists the functions that we'll encounter in the code that operates on mbufs. The macros in Figure 2.19 are shown as function prototypes, not as `#define` statements, to show the data types of the arguments. We will not go through the source code implementation of these routines since they are concerned primarily with manipulating the mbuf data structures and involve no networking issues. Also, there are additional mbuf macros and functions used elsewhere in the Net/3 sources that we don't show in these two figures since we won't encounter them in the text.

In all the prototypes the argument *nowait* is either M_WAIT or M_DONTWAIT, and the argument *type* is one of the MT_*xxx* constants shown in Figure 2.10.

Macro	Description
MCLGET	Get a cluster (an external buffer) and set the data pointer (m_data) of the existing mbuf pointed to by *m* to point to the cluster. If memory for a cluster is not available, the M_EXT flag in the mbuf is not set on return. void **MCLGET**(struct mbuf **m*, int *nowait*);
MFREE	Free the single mbuf pointed to by *m*. If *m* points to a cluster (M_EXT is set), the cluster's reference count is decremented but the cluster is not released until its reference count reaches 0 (as discussed in Section 2.9). On return *m*'s successor (pointed to by m->m_next, which can be null) is stored in *n*. void **MFREE**(struct mbuf **m*, struct mbuf **n*);
MGETHDR	Allocate an mbuf and initialize it as a packet header. This macro is similar to MGET (Figure 2.12) except the M_PKTHDR flag is set and the data pointer (m_data) points to the 100-byte buffer just beyond the packet header. void **MGETHDR**(struct mbuf **m*, int *nowait*, int *type*);
MH_ALIGN	Set the m_data pointer of an mbuf containing a packet header to provide room for an object of size *len* bytes at the end of the mbuf's data area. The data pointer is also longword aligned. void **MH_ALIGN**(struct mbuf **m*, int *len*);
M_PREPEND	Prepend *len* bytes of data in front of the data in the mbuf pointed to by *m*. If room exists in the mbuf, just decrement the pointer (m_data) and increment the length (m_len) by *len* bytes. If there is not enough room, a new mbuf is allocated, its m_next pointer is set to *m*, a pointer to the new mbuf is stored in *m*, and the data pointer of the new mbuf is set so that the *len* bytes of data go at the end of the mbuf (i.e., MH_ALIGN is called). Also, if a new mbuf is allocated and the existing mbuf had its packet header flag set, the packet header is moved from the existing mbuf to the new one. void **M_PREPEND**(struct mbuf **m*, int *len*, int *nowait*);
dtom	Convert the pointer *x*, which must point somewhere within the data area of an mbuf, into a pointer to the beginning of the mbuf. struct mbuf ***dtom**(void **x*);
mtod	Type cast the pointer to the data area of the mbuf pointed to by *m* to *type*. *type* **mtod**(struct mbuf **m*, *type*);

Figure 2.19 Mbuf macros that we'll encounter in the text.

As an example of M_PREPEND, this macro was called when the IP and UDP headers were prepended to the user's data in the transition from Figure 1.7 to Figure 1.8, causing another mbuf to be allocated. But when this macro was called again (in the transition from Figure 1.8 to Figure 2.2) to prepend the Ethernet header, room already existed in the mbuf for the headers.

The data type of the last argument for m_copydata is caddr_t, which stands for "core address." This data type is normally defined in <sys/types.h> to be a char *. It was originally used internally by the kernel, but got externalized when used by certain system calls. For example, the mmap system call, in both 4.4BSD and SVR4, uses caddr_t as the type of the first argument and as the return value type.

Function	Description
m_adj	Remove *len* bytes of data from the mbuf pointed to by *m*. If *len* is positive, that number of bytes is trimmed from the start of the data in the mbuf, otherwise the absolute value of *len* bytes is trimmed from the end of the data in the mbuf. `void` **`m_adj`**`(struct mbuf *`*`m`*`, int `*`len`*`);`
m_cat	Concatenate the mbuf chain pointed to by *n* to the end of the mbuf chain pointed to by *m*. We encounter this function when we describe IP reassembly (Chapter 10). `void` **`m_cat`**`(struct mbuf *`*`m`*`, struct mbuf *`*`n`*`);`
m_copy	A three-argument version of m_copym that implies a fourth argument of M_DONTWAIT. `struct mbuf *`**`m_copy`**`(struct mbuf *`*`m`*`, int `*`offset`*`, int `*`len`*`);`
m_copydata	Copy *len* bytes of data from the mbuf chain pointed to by *m* into the buffer pointed to by *cp*. The copying starts from the specified byte *offset* from the beginning of the data in the mbuf chain. `void` **`m_copydata`**`(struct mbuf *`*`m`*`, int `*`offset`*`, int `*`len`*`, caddr_t `*`cp`*`);`
m_copyback	Copy *len* bytes of data from the buffer pointed to by cp into the mbuf chain pointed to by *m*. The data is stored starting at the specified byte *offset* in the mbuf chain. The mbuf chain is extended with additional mbufs if necessary. `void` **`m_copyback`**`(struct mbuf *`*`m`*`, int `*`offset`*`, int `*`len`*`, caddr_t `*`cp`*`);`
m_copym	Create a new mbuf chain and copy *len* bytes of data starting at *offset* from the mbuf chain pointed to by *m*. A pointer to the new mbuf chain is returned as the value of the function. If *len* equals the constant M_COPYALL, the remainder of the mbuf chain starting at *offset* is copied. We say more about this function in Section 2.9. `struct mbuf *`**`m_copym`**`(struct mbuf *`*`m`*`, int `*`offset`*`, int `*`len`*`, int `*`nowait`*`);`

m_devget	Create a new mbuf chain with a packet header and return the pointer to the chain. The len and rcvif fields in the packet header are set to *len* and *ifp*. The function *copy* is called to copy the data from the device interface (pointed to by *buf*) into the mbuf. If *copy* is a null pointer, the function bcopy is called. *off* is 0 since trailer protocols are no longer supported. We described this function in Section 2.6.
	`struct mbuf *`**`m_devget`**`(char *`*`buf`*`, int `*`len`*`, int `*`off`*`, struct ifnet *`*`ifp`*`,`
	`void (*`*`copy`*`)(const void *, void *, u_int);`

m_free	A function version of the macro MFREE. `struct mbuf *`**`m_free`**`(struct mbuf *`*`m`*`);`
m_freem	Free all the mbufs in the chain pointed to by *m*. `void` **`m_freem`**`(struct mbuf *`*`m`*`);`
m_get	A function version of the MGET macro. We showed this function in Figure 2.12. `struct mbuf *`**`m_get`**`(int `*`nowait`*`, int `*`type`*`);`
m_getclr	This function calls the MGET macro to get an mbuf and then zeros the 108-byte buffer. `struct mbuf *`**`m_getclr`**`(int `*`nowait`*`, int `*`type`*`);`
m_gethdr	A function version of the MGETHDR macro. `struct mbuf *`**`m_gethdr`**`(int `*`nowait`*`, int `*`type`*`);`
m_pullup	Rearrange the existing data in the mbuf chain pointed to by *m* so that the first *len* bytes of data are stored contiguously in the first mbuf in the chain. If this function succeeds, then the mtod macro returns a pointer that correctly references a structure of size *len*. We described this function in Section 2.6. `struct mbuf *`**`m_pullup`**`(struct mbuf *`*`m`*`, int `*`len`*`);`

Figure 2.20 Mbuf functions that we'll encounter in the text.

2.8 Summary of Net/3 Networking Data Structures

This section summarizes the types of data structures we'll encounter in the Net/3 networking code. Other data structures are used in the Net/3 kernel (interested readers should examine the `<sys/queue.h>` header), but the following are the ones we'll encounter in this text.

1. An mbuf chain: a list of mbufs, linked through the `m_next` pointer. We've seen numerous examples of these already.
2. A linked list of mbuf chains with a head pointer only. The mbuf chains are linked using the `m_nextpkt` pointer in the first mbuf of each chain.

   Figure 2.21 shows this type of list. Examples of this data structure are a socket's send buffer and receive buffer.

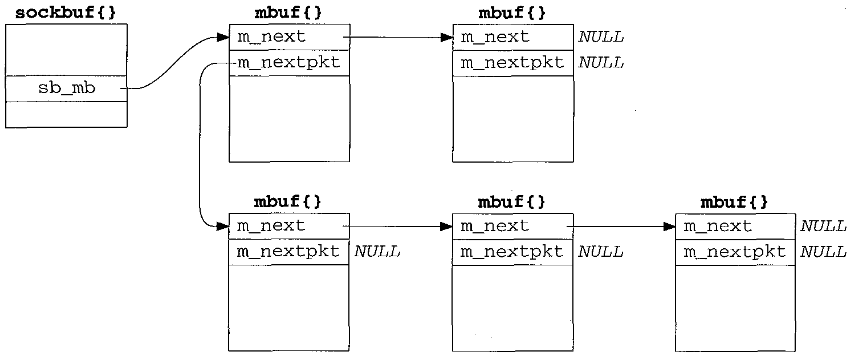


Figure 2.21 Linked list of mbuf chains with head pointer only.

   The top two mbufs form the first record on the queue, and the three mbufs on the bottom form the second record on the queue. For a record-based protocol, such as UDP, we can encounter multiple records per queue, but for a protocol such as TCP that has no record boundaries, we'll find only a single record (one mbuf chain possibly consisting of multiple mbufs) per queue.

   To append an mbuf to the first record on the queue requires going through all the mbufs comprising the first record, until the one with a null `m_next` pointer is encountered. To append an mbuf chain comprising a new record to the queue requires going through all the records until the one with a null `m_nextpkt` pointer is encountered.

3. A linked list of mbuf chains with head and tail pointers.

   Figure 2.22 shows this type of list. We encounter this with the interface queues (Figure 3.13), and showed an earlier example in Figure 2.2.

   The only change in this figure from Figure 2.21 is the addition of a tail pointer, to simplify the addition of new records.

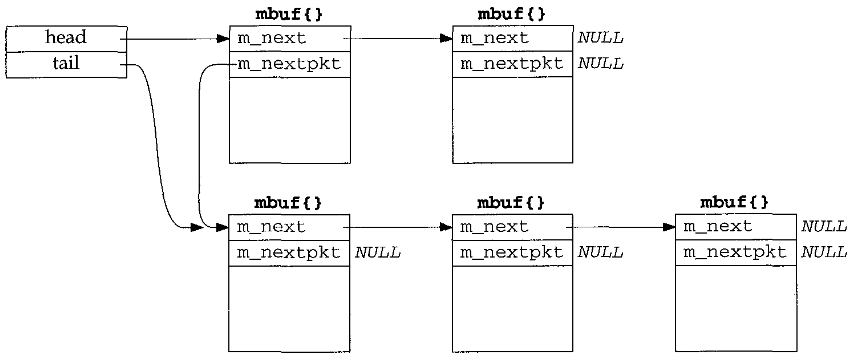


Figure 2.22 Linked list with head and tail pointers.

4. A doubly linked, circular list.

   Figure 2.23 shows this type of list, which we encounter with IP fragmentation and reassembly (Chapter 10), protocol control blocks (Chapter 22), and TCP's out-of-order segment queue (Section 27.9).

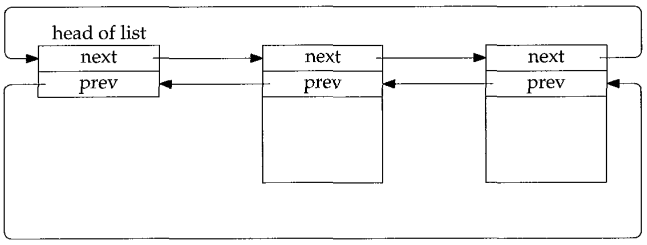


Figure 2.23 Doubly linked, circular list.

The elements in the list are not mbufs—they are structures of some type that are defined with two consecutive pointers: a next pointer followed by a previous pointer. Both pointers must appear at the beginning of the structure. If the list is empty, both the next and previous pointers of the head entry point to the head entry.

For simplicity in the figure we show the back pointers pointing at another back pointer. Obviously all the pointers contain the address of the structure pointed to, that is the address of a forward pointer (since the forward and backward pointer are always at the beginning of the structure).

This type of data structure allows easy traversal either forward or backward, and allows easy insertion or deletion at any point in the list.

The functions `insque` and `remque` (Figure 10.20) are called to insert and delete elements in the list.

2.9 m_copy and Cluster Reference Counts

One obvious advantage with clusters is being able to reduce the number of mbufs required to contain large amounts of data. For example, if clusters were not used, it would require 10 mbufs to contain 1024 bytes of data: the first one with 100 bytes of data, the next eight with 108 bytes of data each, and the final one with 60 bytes of data. There is more overhead involved in allocating and linking 10 mbufs, than there is in allocating a single mbuf containing the 1024 bytes in a cluster. A disadvantage with clusters is the potential for wasted space. In our example it takes 2176 bytes using a cluster (2048 + 128), versus 1280 bytes without a cluster (10 × 128).

An additional advantage with clusters is being able to share a cluster between multiple mbufs. We encounter this with TCP output and the m_copy function, but describe it in more detail now.

As an example, assume the application performs a write of 4096 bytes to a TCP socket. Assuming the socket's send buffer was previously empty, and that the receiver's window is at least 4096, the following operations take place. One cluster is filled with the first 2048 bytes by the socket layer and the protocol's send routine is called. The TCP send routine appends the mbuf to its send buffer, as shown in Figure 2.24, and calls tcp_output.

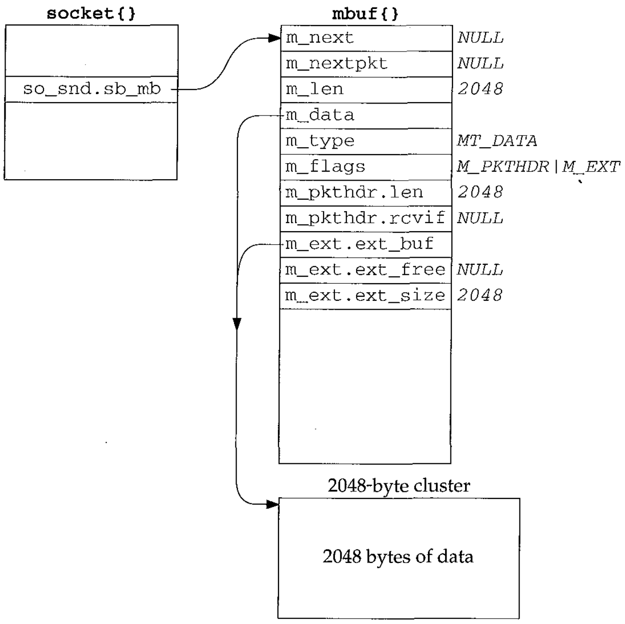


Figure 2.24 TCP socket send buffer containing 2048 bytes of data.

The socket structure contains the sockbuf structure, which holds the head of the list of mbufs on the send buffer: so_snd.sb_mb.

Assuming a TCP maximum segment size (MSS) of 1460 for this connection (typical for an Ethernet), tcp_output builds a segment to send containing the first 1460 bytes of data. It also builds an mbuf containing the IP and TCP headers, leaves room for a link-layer header (16 bytes), and passes this mbuf chain to IP output. The mbuf chain ends up on the interface's output queue, which we show in Figure 2.25.

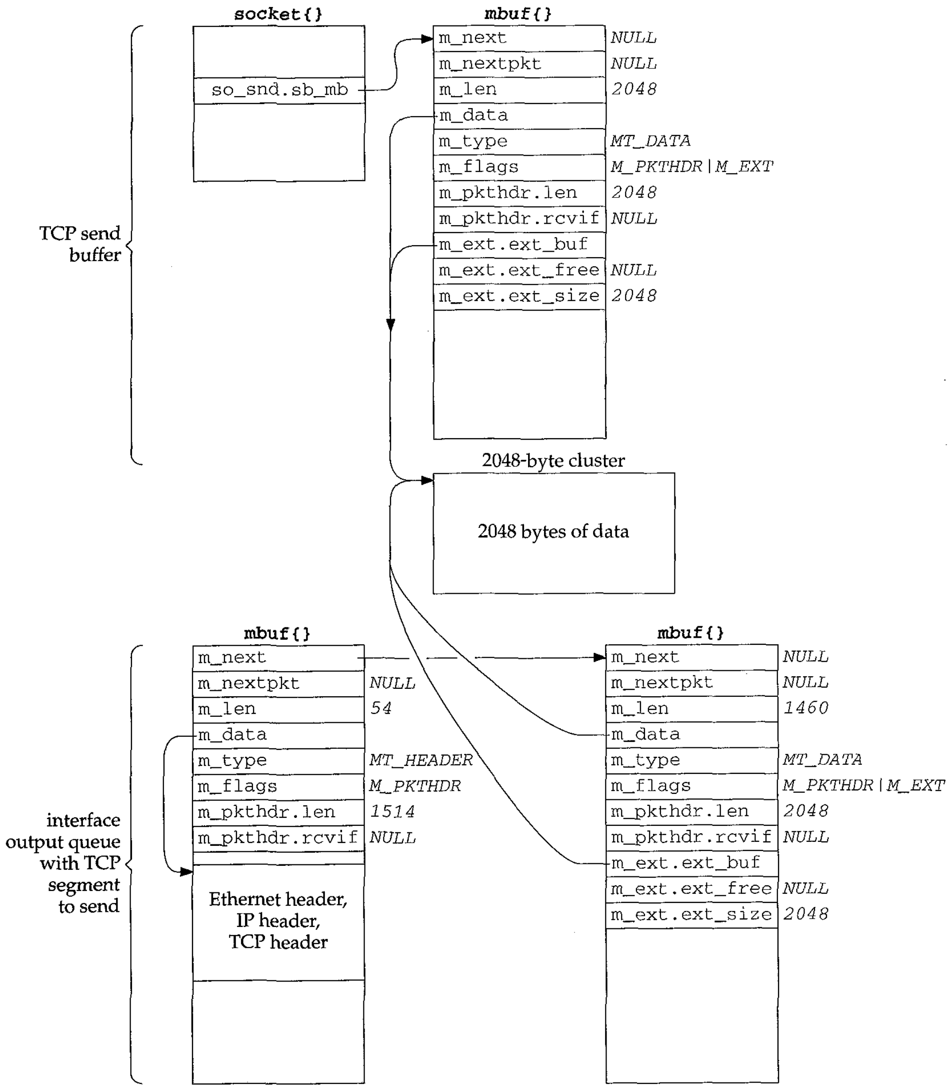


Figure 2.25 TCP socket send buffer and resulting segment on interface's output queue.

In our UDP example in Section 1.9, UDP took the mbuf chain containing the datagram, prepended an mbuf for the protocol headers, and passed the chain to IP output. UDP did not keep the mbuf in its send buffer. TCP cannot do this since TCP is a reliable protocol and it must maintain a *copy* of the data that it sends, until the data is acknowledged by the other end.

In this example `tcp_output` calls the function `m_copy`, requesting a copy be made of 1460 bytes, starting at offset 0 from the start of its send buffer. But since the data is in a cluster, `m_copy` creates an mbuf (the one on the lower right of Figure 2.25) and initializes it to point to the correct place in the existing cluster (the beginning of the cluster in this example). The length of this mbuf is 1460, even though an additional 588 bytes of data are in the cluster. We show the length of the mbuf chain as 1514, accounting for the Ethernet, IP, and TCP headers.

> We also show this mbuf on the lower right of Figure 2.25 containing a packet header, yet this isn't the first mbuf in the chain. When `m_copy` makes a copy of an mbuf that contains a packet header and the copy starts from offset 0 in the original mbuf, the packet header is also copied verbatim. Since this mbuf is not the first mbuf in the chain, this extraneous packet header is just ignored. The `m_pkthdr.len` value of 2048 in this extraneous packet header is also ignored.

This sharing of clusters prevents the kernel from copying the data from one mbuf into another—a big savings. It is implemented by providing a reference count for each cluster that is incremented each time another mbuf points to the cluster, and decremented each time a cluster is released. Only when the reference count reaches 0 is the memory used by the cluster available for some other use. (See Exercise 2.4.)

For example, when the bottom mbuf chain in Figure 2.25 reaches the Ethernet device driver and its contents have been copied to the device, the driver calls `m_freem`. This function releases the first mbuf with the protocol headers and then notices that the second mbuf in the chain points to a cluster. The cluster reference count is decremented, but since its value becomes 1, it is left alone. It cannot be released since it is still in the TCP send buffer.

Continuing our example, `tcp_output` returns after passing the 1460-byte segment to IP, since the remaining 588 bytes in the send buffer don't comprise a full-sized segment. (In Chapter 26 we describe in detail the conditions under which `tcp_output` sends data.) The socket layer continues processing the data from the application: the remaining 2048 bytes are placed into an mbuf with a cluster, TCP's send routine is called again, and this new mbuf is appended to the socket's send buffer. Since a full-sized segment can be sent, `tcp_output` builds another mbuf chain with the protocol headers and the next 1460 bytes of data. The arguments to `m_copy` specify a starting offset of 1460 bytes from the start of the send buffer and a length of 1460 bytes. This is shown in Figure 2.26, assuming the mbuf chain is again on the interface output queue (so the length of the first mbuf in the chain reflects the Ethernet, IP, and TCP headers).

This time the 1460 bytes of data come from two clusters: the first 588 bytes are from the first cluster in the send buffer and the next 872 bytes are from the second cluster in the send buffer. It takes two mbufs to describe these 1460 bytes, but again `m_copy` does not copy the 1460 bytes of data—it references the existing clusters.

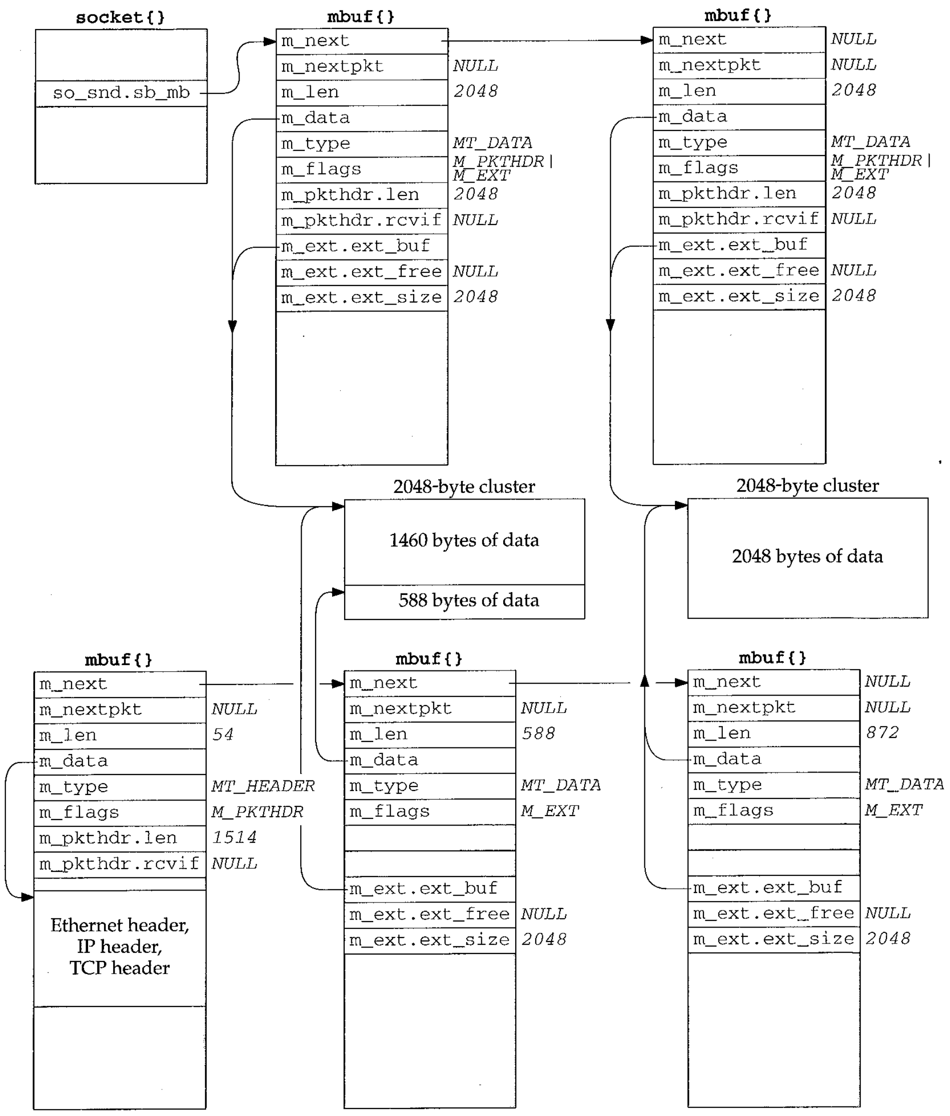


Figure 2.26 Mbuf chain to send next 1460-byte TCP segment.

This time we do not show a packet header with either of the mbufs on the bottom right of Figure 2.26. The reason is that the starting offset in the call to m_copy is nonzero. Also, we show the second mbuf in the socket send buffer containing a packet header, even though it is not the first mbuf in the chain. This is a property of the sosend function, and this extraneous packet header is just ignored.

We encounter the `m_copy` function about a dozen times throughout the text. Although the name implies that a physical copy is made of the data, if the data is contained in a cluster, an additional reference is made to the cluster instead.

2.10 Alternatives

Mbufs are far from perfect and they are berated regularly. Nevertheless, they form the basis for all the Berkeley-derived networking code in use today.

A research implementation of the Internet protocols by Van Jacobson [Partridge 1993] has done away with the complex mbuf data structures in favor of large contiguous buffers. [Jacobson 1993] claims a speed improvement of one to two orders of magnitude, although many other changes were made besides getting rid of mbufs.

The complexity of mbufs is a tradeoff that avoids allocating large fixed buffers that are rarely filled to capacity. At the time mbufs were being designed, a VAX-11/780 with 4 megabytes of memory was a big system, and memory was an expensive resource that needed to be carefully allocated. Today memory is inexpensive, and the focus has shifted toward higher performance and simplicity of code.

The performance of mbufs is also dependent on the amount of data stored in the mbuf. [Hutchinson and Peterson 1991] show that the amount of time required for mbuf processing is nonlinear with respect to the amount of data.

2.11 Summary

We'll encounter mbufs in almost every function in the text. Their main purpose is to hold the user data that travels from the process to the network interface, and vice versa, but mbufs are also used to contain a variety of other miscellaneous data: source and destination addresses, socket options, and so on.

There are four types of mbufs, depending whether the `M_PKTHDR` and `M_EXT` flags are on or off:

- no packet header, with 0 to 108 bytes of data in mbuf itself,
- packet header, with 0 to 100 bytes of data in mbuf itself,
- no packet header, with data in cluster (external buffer), and
- packet header, with data in cluster (external buffer).

We looked at the source code for a few of the mbuf macros and functions, but did not present the source code for all the mbuf routines. Figures 2.19 and 2.20 provide the function prototypes and descriptions of all the mbuf routines that we encounter in the text.

We looked at the operation of two functions that we'll encounter: `m_devget`, which is called by many network device drivers to store a received frame; and `m_pullup`, which is called by all the input routines to place the required protocol headers into contiguous storage in an mbuf.

The clusters (external buffers) pointed to by an mbuf can be shared by m_copy. This is used, for example, by TCP output, because a copy of the data being transmitted must be maintained by the sender until that data is acknowledged by the other end. Sharing clusters through reference counts is a performance improvement over making a physical copy of the data.

Exercises

2.1 In Figure 2.9 the M_COPYFLAGS value was defined. Why was the M_EXT flag not copied?

2.2 In Section 2.6 we listed two reasons that m_pullup can fail. There are really three reasons. Obtain the source code for this function (Appendix B) and discover the additional reason.

2.3 To avoid the problems we described in Section 2.6 with the dtom macro when the data is in a cluster, why not just add a back pointer to the mbuf for each cluster?

2.4 Since the size of an mbuf cluster is a power of 2 (typically 1024 or 2048), space cannot be taken within the cluster for the reference count. Obtain the Net/3 sources (Appendix B) and determine where these reference counts are stored.

2.5 In Figure 2.5 we noted that the two counters m_drops and m_wait are not currently implemented. Modify the mbuf routines to increment these counters when appropriate.

3

Interface Layer

3.1 Introduction

This chapter starts our discussion of Net/3 at the bottom of the protocol stack with the interface layer, which includes the hardware and software that sends and receives packets on locally attached networks.

We use the term *device driver* to refer to the software that communicates with the hardware and *network interface* (or just *interface*) for the hardware and device driver for a particular network.

The Net/3 interface layer attempts to provide a hardware-independent programming interface between the network protocols and the drivers for the network devices connected to a system. The interface layer supports provides for all devices:

- a well-defined set of interface functions,
- a standard set of statistics and control flags,
- a device-independent method of storing protocol addresses, and
- a standard queueing method for outgoing packets.

There is no requirement that the interface layer provide reliable delivery of packets, only a best-effort service is required. Higher protocol layers must compensate for this lack of reliability. This chapter describes the generic data structures maintained for all network interfaces. To illustrate the relevant data structures and algorithms, we refer to three particular network interfaces from Net/3:

1. An AMD 7990 LANCE Ethernet interface: an example of a broadcast-capable local area network.
2. A Serial Line IP (SLIP) interface: an example of a point-to-point network running over asynchronous serial lines.

3. A loopback interface: a logical network that returns all outgoing packets as input packets.

3.2 Code Introduction

The generic interface structures and initialization code are found in three headers and two C files. The device-specific initialization code described in this chapter is found in three different C files. All eight files are listed in Figure 3.1.

File	Description
`sys/socket.h`	address structure definitions
`net/if.h`	interface structure definitions
`net/if_dl.h`	link-level structure definitions
`kern/init_main.c`	system and interface initialization
`net/if.c`	generic interface code
`net/if_loop.c`	loopback device driver
`net/if_sl.c`	SLIP device driver
`hp300/dev/if_le.c`	LANCE Ethernet device driver

Figure 3.1 Files discussed in this chapter.

Global Variables

The global variables introduced in this chapter are described in Figure 3.2.

Variable	Data type	Description
`pdevinit`	`struct pdevinit []`	array of initialization parameters for pseudo-devices such as SLIP and loopback interfaces
`ifnet`	`struct ifnet *`	head of list of `ifnet` structures
`ifnet_addrs`	`struct ifaddr **`	array of pointers to link-level interface addresses
`if_indexlim`	`int`	size of `ifnet_addrs` array
`if_index`	`int`	index of the last configured interface
`ifqmaxlen`	`int`	maximum size of interface output queues
`hz`	`int`	the clock-tick frequency for this system (ticks/second)

Figure 3.2 Global variables introduced in this chapter.

SNMP Variables

The Net/3 kernel collects a wide variety of networking statistics. In most chapters we summarize the statistics and show how they relate to the standard TCP/IP information and statistics defined in the Simple Network Management Protocol Management Information Base (SNMP MIB-II). RFC 1213 [McCloghrie and Rose 1991] describe SNMP MIB-II, which is organized into 10 distinct information groups shown in Figure 3.3.

SNMP Group	Description
System	general information about the system
Interfaces	network interface information
Address Translation	network-address-to-hardware-address-translation tables (deprecated)
IP	IP protocol information
ICMP	ICMP protocol information
TCP	TCP protocol information
UDP	UDP protocol information
EGP	EGP protocol information
Transmission	media-specific information
SNMP	SNMP protocol information

Figure 3.3 *SNMP groups in MIB-II.*

Net/3 does not include an SNMP agent. Instead, an SNMP agent for Net/3 is implemented as a process that accesses the kernel statistics in response to SNMP queries through the mechanism described in Section 2.2.

While most of the MIB-II variables are collected by Net/3 and may be accessed directly by an SNMP agent, others must be derived indirectly. MIB-II variables fall into three categories: (1) simple variables such an integer value, a timestamp, or a byte string; (2) lists of simple variables such as an individual routing entry or an interface description entry; and (3) lists of lists such as the entire routing table and the list of all interface entries.

The ISODE package includes a sample SNMP agent for Net/3. See Appendix B for information about ISODE.

Figure 3.4 shows the one simple variable maintained for the SNMP interface group. We describe the SNMP interface table later in Figure 4.7.

SNMP variable	Net/3 variable	Description
`ifNumber`	`if_index + 1`	`if_index` is the index of the last interface in the system and starts at 0; 1 is added to get `ifNumber`, the number of interfaces in the system.

Figure 3.4 Simple SNMP variable in the interface group.

3.3 `ifnet` Structure

The `ifnet` structure contains information common to all interfaces. During system initialization, a separate `ifnet` structure is allocated for each network device. Every `ifnet` structure has a list of one or more protocol addresses associated with it. Figure 3.5 illustrates the relationship between an interface and its addresses.

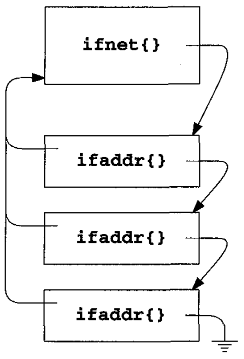


Figure 3.5 Each `ifnet` structure has a list of associated `ifaddr` structures.

The interface in Figure 3.5 is shown with three protocol addresses stored in `ifaddr` structures. Although some network interfaces, such as SLIP, support only a single protocol, others, such as Ethernet, support multiple protocols and need multiple addresses. For example, a system may use a single Ethernet interface for both Internet and OSI protocols. A type field identifies the contents of each Ethernet frame, and since the Internet and OSI protocols employ different addressing schemes, the Ethernet interface must have an Internet address and an OSI address. All the addresses are connected by a linked list (the arrows on the right of Figure 3.5), and each contains a back pointer to the related `ifnet` structure (the arrows on the left of Figure 3.5).

It is also possible for a single network interface to support multiple addresses within a single protocol. For example, two Internet addresses may be assigned to a single Ethernet interface in Net/3.

This feature first appeared in Net/2. Having two IP addresses for an interface is useful when renumbering a network. During a transition period, the interface can accept packets addressed to the old and new addresses.

The `ifnet` structure is large so we describe it in five sections:

- implementation information,
- hardware information,
- interface statistics,
- function pointers, and
- the output queue.

Figure 3.6 shows the implementation information contained in the `ifnet` structure.

80–82 `if_next` joins the `ifnet` structures for all the interfaces into a linked list. The `if_attach` function constructs the list during system initialization. `if_addrlist` points to the list of `ifaddr` structures for the interface (Figure 3.16). Each `ifaddr` structure holds addressing information for a protocol that expects to communicate through the interface.

if.h

```
80 struct ifnet {
81     struct ifnet *if_next;      /* all struct ifnets are chained */
82     struct ifaddr *if_addrlist; /* linked list of addresses per if */
83     char   *if_name;            /* name, e.g. 'le' or 'lo' */
84     short   if_unit;            /* sub-unit for lower level driver */
85     u_short if_index;           /* numeric abbreviation for this if  */
86     short   if_flags;           /* Figure 3.7 */
87     short   if_timer;           /* time 'til if_watchdog called */
88     int     if_pcount;          /* number of promiscuous listeners */
89     caddr_t if_bpf;             /* packet filter structure */
```

if.h

Figure 3.6 `ifnet` *structure: implementation information.*

Common interface information

83–86 `if_name` is a short string that identifies the interface type, and `if_unit` identifies multiple instances of the same type. For example, if a system had two SLIP interfaces, both would have an `if_name` consisting of the 2 bytes "`sl`" and an `if_unit` of 0 for the first interface and 1 for the second. `if_index` uniquely identifies the interface within the kernel and is used by the `sysctl` system call (Section 19.14) as well as in the routing domain.

Sometimes an interface is not uniquely identified by a protocol address. For example, several SLIP connections can have the same local IP address. In these cases, `if_index` specifies the interface explicitly.

`if_flags` specifies the operational state and properties of the interface. A process can examine all the flags but cannot change the flags marked in the "Kernel only" column in Figure 3.7. The flags are accessed with the `SIOCGIFFLAGS` and `SIOCSIFFLAGS` commands described in Section 4.4.

`if_flags`	Kernel only	Description
IFF_BROADCAST	•	the interface is for a broadcast network
IFF_MULTICAST	•	the interface supports multicasting
IFF_POINTOPOINT	•	the interface is for a point-to-point network
IFF_LOOPBACK		the interface is for a loopback network
IFF_OACTIVE	•	a transmission is in progress
IFF_RUNNING	•	resources are allocated for this interface
IFF_SIMPLEX	•	the interface cannot receive its own transmissions
IFF_LINK0	see text	defined by device driver
IFF_LINK1	see text	defined by device driver
IFF_LINK2	see text	defined by device driver
IFF_ALLMULTI		the interface is receiving all multicast packets
IFF_DEBUG		debugging is enabled for the interface
IFF_NOARP		don't use ARP on this interface
IFF_NOTRAILERS		avoid using trailer encapsulation
IFF_PROMISC		the interface receives all network packets
IFF_UP		the interface is operating

Figure 3.7 `if_flags` values.

The IFF_BROADCAST and IFF_POINTOPOINT flags are mutually exclusive.

The macro IFF_CANTCHANGE is a bitwise OR of all the flags in the "Kernel only" column.

The device-specific flags (IFF_LINK*x*) may or may not be modifiable by a process depending on the device. For example, Figure 3.29 shows how these flags are defined by the SLIP driver.

Interface timer

87 if_timer is the time in seconds until the kernel calls the if_watchdog function for the interface. This function may be used by the device driver to collect interface statistics at regular intervals or to reset hardware that isn't operating correctly.

BSD Packet Filter

88–89 The next two members, if_pcount and if_bpf, support the *BSD Packet Filter* (BPF). Through BPF, a process can receive copies of packets transmitted or received by an interface. As we discuss the device drivers, we also describe how packets are passed to BPF. BPF itself is described in Chapter 31.

The next section of the ifnet structure, shown in Figure 3.8, describes the hardware characteristics of the interface.

if.h
```
 90     struct if_data {
 91 /* generic interface information */
 92         u_char  ifi_type;       /* Figure 3.9 */
 93         u_char  ifi_addrlen;    /* media address length */
 94         u_char  ifi_hdrlen;     /* media header length */
 95         u_long  ifi_mtu;        /* maximum transmission unit */
 96         u_long  ifi_metric;     /* routing metric (external only) */
 97         u_long  ifi_baudrate;   /* linespeed */

                               /* other ifnet members */

138 #define if_mtu      if_data.ifi_mtu
139 #define if_type     if_data.ifi_type
140 #define if_addrlen  if_data.ifi_addrlen
141 #define if_hdrlen   if_data.ifi_hdrlen
142 #define if_metric   if_data.ifi_metric
143 #define if_baudrate if_data.ifi_baudrate
```
if.h

Figure 3.8 ifnet structure: interface characteristics.

Net/3 and this text use the short names provided by the #define statements on lines 138 through 143 to specify the ifnet members.

Interface characteristics

90–92 if_type specifies the hardware address type supported by the interface. Figure 3.9 lists several common values from net/if_types.h.

if_type	Description
IFT_OTHER	unspecified
IFT_ETHER	Ethernet
IFT_ISO88023	IEEE 802.3 Ethernet (CMSA/CD)
IFT_ISO88025	IEEE 802.5 token ring
IFT_FDDI	Fiber Distributed Data Interface
IFT_LOOP	loopback interface
IFT_SLIP	serial line IP

Figure 3.9 if_type: data-link types.

93–94 if_addrlen is the length of the datalink address and if_hdrlen is the length of the header attached to any outgoing packet by the hardware. An Ethernet network, for example, has an address length of 6 bytes and a header length of 14 bytes (Figure 4.8).

95 if_mtu is the maximum transmission unit of the interface: the size in bytes of the largest unit of data that the interface can transmit in a single output operation. This is an important parameter that controls the size of packets created by the network and transport protocols. For Ethernet, the value is 1500.

96–97 if_metric is usually 0; a higher value makes routes through the interface less favorable. if_baudrate specifies the transmission speed of the interface. It is set only by the SLIP interface.

Interface statistics are collected by the next group of members in the ifnet structure shown in Figure 3.10.

Interface statistics

98–111 Most of these statistics are self-explanatory. if_collisions is incremented when packet transmission is interrupted by another transmission on shared media such as Ethernet. if_noproto counts the number of packets that can't be processed because the protocol is not supported by the system or the interface (e.g., an OSI packet that arrives at a system that supports only IP). The SLIP interface increments if_noproto if a non-IP packet is placed on its output queue.

These statistics were not part of the ifnet structure in Net/1. They were added to support the standard SNMP MIB-II variables for interfaces.

if_iqdrops is accessed only by the SLIP device driver. SLIP and the other network drivers increment if_snd.ifq_drops (Figure 3.13) when IF_DROP is called. ifq_drops was already in the BSD software when the SNMP statistics were added. The ISODE SNMP agent ignores if_iqdrops and uses ifsnd.ifq_drops.

Change timestamp

112–113 if_lastchange records the last time any of the statistics were changed.

if.h

```
 98 /* volatile statistics */
 99         u_long  ifi_ipackets;    /* #packets received on interface */
100         u_long  ifi_ierrors;     /* #input errors on interface */
101         u_long  ifi_opackets;    /* #packets sent on interface */
102         u_long  ifi_oerrors;     /* #output errors on interface */
103         u_long  ifi_collisions;  /* #collisions on csma interfaces */
104         u_long  ifi_ibytes;      /* #bytes received */
105         u_long  ifi_obytes;      /* #bytes sent */
106         u_long  ifi_imcasts;     /* #packets received via multicast */
107         u_long  ifi_omcasts;     /* #packets sent via multicast */
108         u_long  ifi_iqdrops;     /* #packets dropped on input, for this
109                                     interface */
110         u_long  ifi_noproto;     /* #packets destined for unsupported
111                                     protocol */
112         struct timeval ifi_lastchange;  /* last updated */
113     } if_data;

                                /* other ifnet members */

144 #define if_ipackets if_data.ifi_ipackets
145 #define if_ierrors  if_data.ifi_ierrors
146 #define if_opackets if_data.ifi_opackets
147 #define if_oerrors  if_data.ifi_oerrors
148 #define if_collisions   if_data.ifi_collisions
149 #define if_ibytes   if_data.ifi_ibytes
150 #define if_obytes   if_data.ifi_obytes
151 #define if_imcasts  if_data ifi_imcasts
152 #define if_omcasts  if_data.ifi_omcasts
153 #define if_iqdrops  if_data.ifi_iqdrops
154 #define if_noproto  if_data.ifi_noproto
155 #define if_lastchange   if_data.ifi_lastchange
```

if.h

Figure 3.10 `ifnet` structure: interface statistics.

Once again, Net/3 and this text use the short names provided by the `#define` statements on lines 144 through 155 to specify the `ifnet` members.

The next section of the `ifnet` structure, shown in Figure 3.11, contains pointers to the standard interface-layer functions, which isolate device-specific details from the network layer. Each network interface implements these functions as appropriate for the particular device.

Interface functions

114–129 Each device driver initializes its own `ifnet` structure, including the seven function pointers, at system initialization time. Figure 3.12 describes the generic functions.

We will see the comment `/* XXX */` throughout Net/3. It is a warning to the reader that the code is obscure, contains nonobvious side effects, or is quick solution to a more difficult problem. In this case, it indicates that `if_done` is not used in Net/3.

if.h
```
/* procedure handles */
    int     (*if_init)          /* init routine */
            (int);
    int     (*if_output)        /* output routine (enqueue) */
            (struct ifnet *, struct mbuf *, struct sockaddr *,
             struct rtentry *);
    int     (*if_start)         /* initiate output routine */
            (struct ifnet *);
    int     (*if_done)          /* output complete routine */
            (struct ifnet *);   /* (XXX not used; fake prototype) */
    int     (*if_ioctl)         /* ioctl routine */
            (struct ifnet *, int, caddr_t);
    int     (*if_reset)
            (int);              /* new autoconfig will permit removal */
    int     (*if_watchdog)      /* timer routine */
            (int);
```
if.h

Figure 3.11 ifnet structure: interface procedures.

Function	Description
if_init	initialize the interface
if_output	queue outgoing packets for transmission
if_start	initiate transmission of packets
if_done	cleanup after transmission completes (not used)
if_ioctl	process I/O control commands
if_reset	reset the interface device
if_watchdog	periodic interface routine

Figure 3.12 ifnet structure: function pointers.

In Chapter 4 we look at the device-specific functions for the Ethernet, SLIP, and loopback interfaces, which the kernel calls indirectly through the pointers in the ifnet structure. For example, if ifp points to an ifnet structure,

```
(*ifp->if_start)(ifp)
```

calls the if_start function of the device driver associated with the interface.

The remaining member of the ifnet structure is the output queue for the interface and is shown in Figure 3.13.

if.h
```
    struct ifqueue {
        struct mbuf *ifq_head;
        struct mbuf *ifq_tail;
        int     ifq_len;        /* current length of queue */
        int     ifq_maxlen;     /* maximum length of queue */
        int     ifq_drops;      /* packets dropped because of full queue */
    } if_snd;                   /* output queue */
};
```
if.h

Figure 3.13 ifnet structure: the output queue.

130–137 if_snd is the queue of outgoing packets for the interface. Each interface has its own ifnet structure and therefore its own output queue. ifq_head points to the first packet on the queue (the next one to be output), ifq_tail points to the last packet on the queue, if_len is the number of packets currently on the queue, and ifq_maxlen is the maximum number of buffers allowed on the queue. This maximum is set to 50 (from the global integer ifqmaxlen, which is initialized at compile time from IFQ_MAXLEN) unless the driver changes it. The queue is implemented as a linked list of mbuf chains. ifq_drops counts the number of packets discarded because the queue was full. Figure 3.14 lists the macros and functions that access a queue.

Function	Description
IF_QFULL	Is *ifq* full? int **IF_QFULL**(struct ifqueue **ifq*);
IF_DROP	IF_DROP only increments the ifq_drops counter associated with *ifq*. The name is misleading; the *caller* drops the packet. void **IF_DROP**(struct ifqueue **ifq*);
IF_ENQUEUE	Add the packet *m* to the end of the *ifq* queue. Packets are linked together by m_nextpkt in the mbuf header. void **IF_ENQUEUE**(struct ifqueue **ifq*, struct mbuf **m*);
IF_PREPEND	Insert the packet *m* at the front of the *ifq* queue. void **IF_PREPEND**(struct ifqueue **ifq*, struct mbuf **m*);
IF_DEQUEUE	Take the first packet off the *ifq* queue. *m* points to the dequeued packet or is null if the queue was empty. void **IF_DEQUEUE**(struct ifqueue **ifq*, struct mbuf **m*);
if_qflush	Discard all packets on the queue *ifq*, for example, when an interface is shut down. void **if_qflush**(struct ifqueue **ifq*);

Figure 3.14 ifqueue routines.

The first five routines are macros defined in net/if.h and the last routine, if_qflush, is a function defined in net/if.c. The macros often appear in sequences such as:

```
s = splimp();
if (IF_QFULL(inq)) {
    IF_DROP(inq);         /* queue is full, drop new packet */
    m_freem(m);
} else
    IF_ENQUEUE(inq, m);   /* there is room, add to end of queue */
splx(s);
```

This code fragment attempts to add a packet to the queue. If the queue is full, IF_DROP increments ifq_drops and the packet is discarded. Reliable protocols such as TCP will retransmit discarded packets. Applications using an unreliable protocol such as UDP must detect and handle the retransmission on their own.

Access to the queue is bracketed by splimp and splx to block network interrupts and to prevent the network interrupt service routines from accessing the queue while it is in an indeterminate state.

m_freem is called before splx because the mbuf code has a critical section that runs at splimp. It would be wasted effort to call splx before m_free only to enter another critical section during m_freem (Section 2.5).

3.4 ifaddr Structure

The next structure we look at is the interface address structure, ifaddr, shown in Figure 3.15. Each interface maintains a linked list of ifaddr structures because some data links, such as Ethernet, support more than one protocol. A separate ifaddr structure describes each address assigned to the interface, usually one address per protocol. Another reason to support multiple addresses is that many protocols, including TCP/IP, support multiple addresses assigned to a single physical interface. Although Net/3 supports this feature, many implementations of TCP/IP do not.

if.h
```
217 struct ifaddr {
218         struct  ifaddr *ifa_next;        /* next address for interface */
219         struct  ifnet *ifa_ifp;          /* back-pointer to interface */
220         struct  sockaddr *ifa_addr;      /* address of interface */
221         struct  sockaddr *ifa_dstaddr;   /* other end of p-to-p link */
222 #define ifa_broadaddr   ifa_dstaddr      /* broadcast address interface */
223         struct  sockaddr *ifa_netmask;   /* used to determine subnet */
224         void    (*ifa_rtrequest)();      /* check or clean routes */
225         u_short ifa_flags;               /* mostly rt_flags for cloning */
226         short   ifa_refcnt;              /* references to this structure */
227         int     ifa_metric;              /* cost for this interface */
228 };
```
if.h

Figure 3.15 ifaddr structure.

217–219 The ifaddr structure links all addresses assigned to an interface together by ifa_next and contains a pointer, ifa_ifp, back to the interface's ifnet structure. Figure 3.16 shows the relationship between the ifnet structures and the ifaddr structures.

220 ifa_addr points to a protocol address for the interface and ifa_netmask points to a bit mask that selects the network portion of ifa_addr. Bits that represent the network portion of the address are set to 1 in the mask, and the host portion of the address is set to all 0 bits. Both addresses are stored as sockaddr structures (Section 3.5). Figure 3.38 shows an address and its related mask structure. For IP addresses, the mask selects the network and subnet portions of the IP address.

221–223 ifa_dstaddr (or its alias ifa_broadaddr) points to the protocol address of the interface at the other end of a point-to-point link or to the broadcast address assigned to

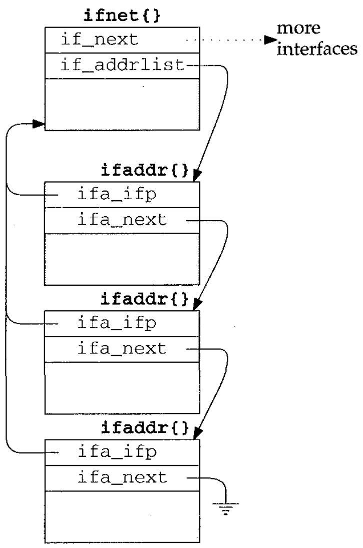


Figure 3.16 ifnet and ifaddr structures.

the interface on a broadcast network such as Ethernet. The mutually exclusive flags IFF_BROADCAST and IFF_POINTOPOINT (Figure 3.7) in the interface's ifnet structure specify the applicable name.

224–228 ifa_rtrequest, ifa_flags, and ifa_metric support routing lookups for the interface.

ifa_refcnt counts references to the ifaddr structure. The macro IFAFREE only releases the structure when the reference count drops to 0, such as when addresses are deleted with the SIOCDIFADDR ioctl command. The ifaddr structures are reference-counted because they are shared by the interface and routing data structures.

> IFAFREE decrements the counter and returns if there are other references. This is the common case and avoids a function call overhead for all but the last reference. If this is the last reference, IFAFREE calls the function ifafree, which releases the structure.

3.5 sockaddr Structure

Addressing information for an interface consists of more than a single host address. Net/3 maintains host, broadcast, and network masks in structures derived from a generic sockaddr structure. By using a generic structure, hardware and protocol-specific addressing details are hidden from the interface layer.

Figure 3.17 shows the current definition of the structure as well as the definition from earlier BSD releases—an osockaddr structure.

socket.h

```
120 struct sockaddr {
121     u_char  sa_len;             /* total length */
122     u_char  sa_family;          /* address family (Figure 3.19) */
123     char    sa_data[14];        /* actually longer; address value */
124 };

271 struct osockaddr {
272     u_short sa_family;          /* address family (Figure 3.19) */
273     char    sa_data[14];        /* up to 14 bytes of direct address */
274 };
```

socket.h

Figure 3.17 sockaddr and osockaddr structures.

Figure 3.18 illustrates the organization of these structures.

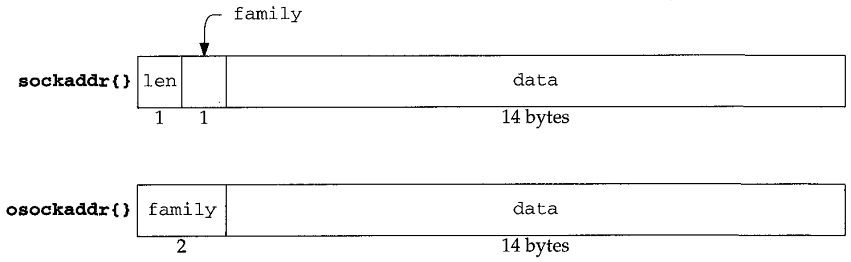


Figure 3.18 sockaddr and osockaddr structures (sa_ prefix dropped).

In many figures, we omit the common prefix in member names. In this case, we've dropped the sa_ prefix.

sockaddr structure

120–124 Every protocol has its own address format. Net/3 handles generic addresses in a sockaddr structure. sa_len specifies the length of the address (OSI and Unix domain protocols have variable-length addresses) and sa_family specifies the type of address. Figure 3.19 lists the *address family* constants that we encounter.

sa_family	Protocol
AF_INET	Internet
AF_ISO, AF_OSI	OSI
AF_UNIX	Unix
AF_ROUTE	routing table
AF_LINK	data link
AF_UNSPEC	(see text)

Figure 3.19 sa_family constants.

The contents of a sockaddr when AF_UNSPEC is specified depends on the context. In most cases, it contains an Ethernet hardware address.

The sa_len and sa_family members allow protocol-independent code to manipulate variable-length sockaddr structures from multiple protocol families. The remaining member, sa_data, contains the address in a protocol-dependent format. sa_data is defined to be an array of 14 bytes, but when the sockaddr structure overlays a larger area of memory sa_data may be up to 253 bytes long. sa_len is only a single byte, so the size of the entire address including sa_len and sa_family must be less than 256 bytes.

This is a common C technique that allows the programmer to consider the last member in a structure to have a variable length.

Each protocol defines a specialized sockaddr structure that duplicates the sa_len and sa_family members but defines the sa_data member as required for that protocol. The address stored in sa_data is a transport address; it contains enough information to identify multiple communication end points on the same host. In Chapter 6 we look at the Internet address structure sockaddr_in, which consists of an IP address and a port number.

osockaddr structure

271–274 The osockaddr structure is the definition of a sockaddr before the 4.3BSD Reno release. Since the length of an address was not explicitly available in this definition, it was not possible to write protocol-independent code to handle variable-length addresses. The desire to include the OSI protocols, which utilize variable-length addresses, motivated the change in the sockaddr definition seen in Net/3. The osockaddr structure is supported for binary compatibility with previously compiled programs.

We have omitted the binary compatibility code from this text.

3.6 ifnet and ifaddr Specialization

The ifnet and ifaddr structures contain general information applicable to all network interfaces and protocol addresses. To accommodate additional device and protocol-specific information, each driver defines and each protocol allocates a specialized version of the ifnet and ifaddr structures. These specialized structures always contain an ifnet or ifaddr structure as their first member so that the common information can be accessed without consideration for the additional specialized information.

Most device drivers handle multiple interfaces of the same type by allocating an array of its specialized ifnet structures, but others (such as the loopback driver) handle only one interface. Figure 3.20 shows the arrangement of specialized ifnet structures for our sample interfaces.

Notice that each device's structure begins with an ifnet structure, followed by all the device-dependent data. The loopback interface declares only an ifnet structure, since it doesn't require any device-dependent data. We show the Ethernet and SLIP driver's softc structures with the array index of 0 in Figure 3.20 since both drivers

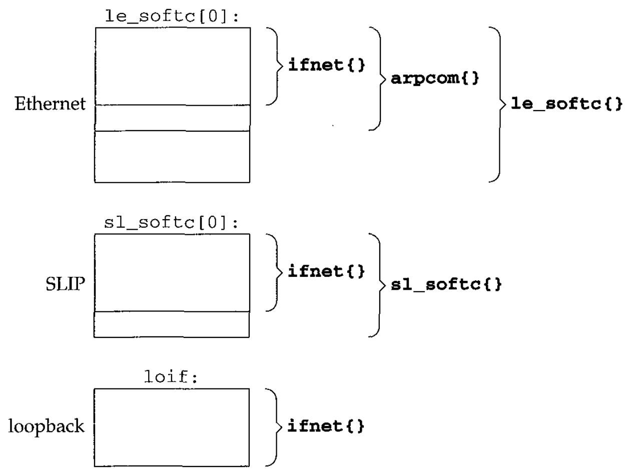


Figure 3.20 Arrangement of ifnet structures within device-dependent structures.

support multiple interfaces. The maximum number of interfaces of any given type is limited by a configuration parameter when the kernel is built.

The arpcom structure (Figure 3.26) is common to all Ethernet drivers and contains information for the Address Resolution Protocol (ARP) and Ethernet multicasting. The le_softc structure (Figure 3.25) contains additional information unique to the LANCE Ethernet device driver.

Each protocol stores addressing information for each interface in a list of specialized ifaddr structures. The Internet protocols use an in_ifaddr structure (Section 6.5) and the OSI protocols an iso_ifaddr structure. In addition to protocol addresses, the kernel assigns each interface a *link-level address* when the interface is initialized, which identifies the interface within the kernel.

The kernel constructs the link-level address by allocating memory for an ifaddr structure and two sockaddr_dl structures—one for the link-level address itself and one for the link-level address mask. The sockaddr_dl structures are accessed by OSI, ARP, and the routing algorithms. Figure 3.21 shows an Ethernet interface with a link-level address, an Internet address, and an OSI address. The construction and initialization of the link-level address (the ifaddr and the two sockaddr_dl structures) is described in Section 3.11.

3.7 Network Initialization Overview

All the structures we have described are allocated and attached to each other during kernel initialization. In this section we give a broad overview of the initialization steps. In later sections we describe the specific device- and protocol-initialization steps.

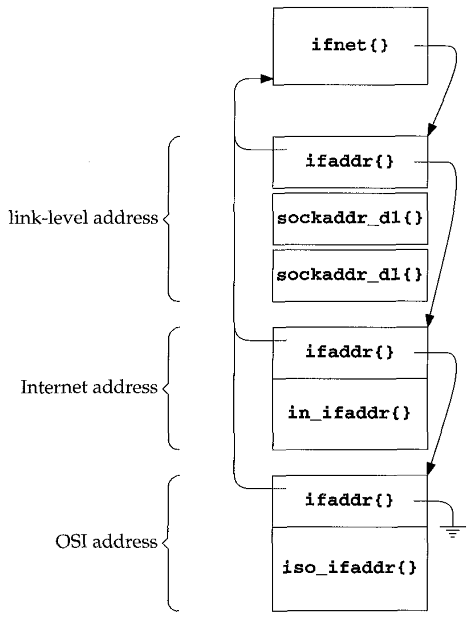


Figure 3.21 An interface address list containing link-level, Internet, and OSI addresses.

Some devices, such as the SLIP and loopback interfaces, are implemented entirely in software. These *pseudo-devices* are represented by a `pdevinit` structure (Figure 3.22) stored in the global `pdevinit` array. The array is constructed during kernel configuration. For example:

```
struct pdevinit pdevinit[] = {
    { slattach, 1 },
    { loopattach, 1 },
    { 0, 0 }
};
```

device.h

```
120 struct pdevinit {
121     void    (*pdev_attach) (int);   /* attach function */
122     int     pdev_count;          /* number of devices */
123 };
```

device.h

Figure 3.22 `pdevinit` structure.

120–123 In the `pdevinit` structures for the SLIP and the loopback interface, `pdev_attach` is set to `slattach` and `loopattach` respectively. When the attach function is called, `pdev_count` is passed as the only argument and specifies the number of devices to create. Only one loopback device is created but multiple SLIP devices may be created if the administrator configures the SLIP entry accordingly.

The network initialization functions from `main` are shown in Figure 3.23.

```
                                                                    init_main.c
 70 main(framep)
 71 void    *framep;
 72 {

                                      /* nonnetwork code */

 96     cpu_startup();              /* locate and initialize devices */

                                      /* nonnetwork code */

172     /* Attach pseudo-devices. (e.g., SLIP and loopback interfaces) */
173     for (pdev = pdevinit; pdev->pdev_attach != NULL; pdev++)
174         (*pdev->pdev_attach) (pdev->pdev_count);

175     /*
176      * Initialize protocols.  Block reception of incoming packets
177      * until everything is ready.
178      */
179     s = splimp();
180     ifinit();                   /* initialize network interfaces */
181     domaininit();               /* initialize protocol domains */
182     splx(s);

                                      /* nonnetwork code */

231     /* The scheduler is an infinite loop. */
232     scheduler();
233     /* NOTREACHED */
234 }
                                                                    init_main.c
```

Figure 3.23 `main` function: network initialization.

70–96 `cpu_startup` locates and initializes all the hardware devices connected to the system, including any network interfaces.

97–174 After the kernel initializes the hardware devices, it calls each of the `pdev_attach` functions contained within the `pdevinit` array.

175–234 `ifinit` and `domaininit` finish the initialization of the network interfaces and protocols and `scheduler` begins the kernel process scheduler. `ifinit` and `domaininit` are described in Chapter 7.

In the following sections we describe the initialization of the Ethernet, SLIP, and loopback interfaces.

3.8 Ethernet Initialization

As part of `cpu_startup`, the kernel locates any attached network devices. The details of this process are beyond the scope of this text. Once a device is identified, a device-specific initialization function is called. Figure 3.24 shows the initialization functions for our three sample interfaces.

Device	Initialization Function
LANCE Ethernet	`leattach`
SLIP	`slattach`
loopback	`loopattach`

Figure 3.24 Network interface initialization functions.

Each device driver for a network interface initializes a specialized `ifnet` structure and calls `if_attach` to insert the structure into the linked list of interfaces. The `le_softc` structure shown in Figure 3.25 is the specialized `ifnet` structure for our sample Ethernet driver (Figure 3.20).

if_le.c
```
69 struct le_softc {
70     struct arpcom sc_ac;         /* common Ethernet structures */
71 #define sc_if   sc_ac.ac_if      /* network-visible interface */
72 #define sc_addr sc_ac.ac_enaddr /* hardware Ethernet address */


                            /* device-specific members */


95 } le_softc[NLE];
```
if_le.c

Figure 3.25 `le_softc` structure.

`le_softc` structure

69–95 An array of `le_softc` structures (with `NLE` elements) is declared in `if_le.c`. Each structure starts with `sc_ac`, an `arpcom` structure common to all Ethernet interfaces, followed by device-specific members. The `sc_if` and `sc_addr` macros simplify access to the `ifnet` structure and Ethernet address within the `arpcom` structure, `sc_ac`, shown in Figure 3.26.

if_ether.h
```
 95 struct arpcom {
 96     struct ifnet ac_if;          /* network-visible interface */
 97     u_char  ac_enaddr[6];        /* ethernet hardware address */
 98     struct in_addr ac_ipaddr;    /* copy of ip address - XXX  */
 99     struct ether_multi *ac_multiaddrs;  /* list of ether multicast addrs */
100     int     ac_multicnt;         /* length of ac_multiaddrs list */
101 };
```
if_ether.h

Figure 3.26 `arpcom` structure.

arpcom structure

95–101 The first member of the arpcom structure, ac_if, is an ifnet structure as shown in Figure 3.20. ac_enaddr is the Ethernet hardware address copied by the LANCE device driver from the hardware when the kernel locates the device during cpu_startup. For our sample driver, this occurs in the leattach function (Figure 3.27). ac_ipaddr is the *last* IP address assigned to the device. We discuss address assignment in Section 6.6, where we'll see that an interface can have several IP addresses. See also Exercise 6.3. ac_multiaddrs is a list of Ethernet multicast addresses represented by ether_multi structures. ac_multicnt counts the entries in the list. The multicast list is discussed in Chapter 12.

Figure 3.27 shows the initialization code for the LANCE Ethernet driver.

106–115 The kernel calls leattach once for each LANCE card it finds in the system.

> The single argument points to an hp_device structure, which contains HP-specific information since this driver is written for an HP workstation.

le points to the specialized ifnet structure for the card (Figure 3.20) and ifp points to the first member of that structure, sc_if, a generic ifnet structure. The device-specific initializations are not included in Figure 3.27 and are not discussed in this text.

Copy the hardware address from the device

126–137 For the LANCE device, the Ethernet address assigned by the manufacturer is copied from the device to sc_addr (which is sc_ac.ac_enaddr—see Figure 3.26) one nibble (4 bits) at a time in this for loop.

> lestd is a device-specific table of offsets to locate information relative to hp_addr, which points to LANCE-specific information.

The complete address is output to the console by the printf statement to indicate that the device exists and is is operational.

Initialize the ifnet structure

150–157 leattach copies the device unit number from the hp_device structure into if_unit to identify multiple interfaces of the same type. if_name is "le" for this device; if_mtu is 1500 bytes (ETHERMTU), the maximum transmission unit for Ethernet; if_init, if_reset, if_ioctl, if_output, and if_start all point to device-specific implementations of the generic functions that control the network interface. Section 4.1 describes these functions.

158 All Ethernet devices support IFF_BROADCAST. The LANCE device does not receive its own transmissions, so IFF_SIMPLEX is set. The driver and hardware supports multicasting so IFF_MULTICAST is also set.

159–162 bpfattach registers the interface with BPF and is described with Figure 31.8. The if_attach function inserts the initialized ifnet structure into the linked list of interfaces (Section 3.11).

if_le.c

```
leattach(hd)
struct hp_device *hd;
{
    struct lereg0 *ler0;
    struct lereg2 *ler2;
    struct lereg2 *lemem = 0;
    struct le_softc *le = &le_softc[hd->hp_unit];
    struct ifnet *ifp = &le->sc_if;
    char   *cp;
    int     i;

                            /* device-specific code */

    /*
     * Read the ethernet address off the board, one nibble at a time.
     */
    cp = (char *) (lestd[3] + (int) hd->hp_addr);
    for (i = 0; i < sizeof(le->sc_addr); i++) {
        le->sc_addr[i] = (*++cp & 0xF) << 4;
        cp++;
        le->sc_addr[i] |= *++cp & 0xF;
        cp++;
    }
    printf("le%d: hardware address %s\n", hd->hp_unit,
           ether_sprintf(le->sc_addr));

                            /* device-specific code */

    ifp->if_unit = hd->hp_unit;
    ifp->if_name = "le";
    ifp->if_mtu = ETHERMTU;
    ifp->if_init = leinit;
    ifp->if_reset = lereset;
    ifp->if_ioctl = leioctl;
    ifp->if_output = ether_output;
    ifp->if_start = lestart;
    ifp->if_flags = IFF_BROADCAST | IFF_SIMPLEX | IFF_MULTICAST;
    bpfattach(&ifp->if_bpf, ifp, DLT_EN10MB, sizeof(struct ether_header));
    if_attach(ifp);
    return (1);
}
```

if_le.c

Figure 3.27 leattach function.

3.9 SLIP Initialization

The SLIP interface relies on a standard asynchronous serial device initialized within the call to cpu_startup. The SLIP pseudo-device is initialized when main calls slattach indirectly through the pdev_attach pointer in SLIP's pdevinit structure.

Each SLIP interface is described by an `sl_softc` structure shown in Figure 3.28.

if_slvar.h
```
43 struct sl_softc {
44     struct ifnet sc_if;          /* network-visible interface */
45     struct ifqueue sc_fastq;     /* interactive output queue */
46     struct tty *sc_ttyp;         /* pointer to tty structure */
47     u_char *sc_mp;               /* pointer to next available buf char */
48     u_char *sc_ep;               /* pointer to last available buf char */
49     u_char *sc_buf;              /* input buffer */
50     u_int   sc_flags;            /* Figure 3.29 */
51     u_int   sc_escape;           /* =1 if last char input was FRAME_ESCAPE */
52     struct slcompress sc_comp;   /* tcp compression data */
53     caddr_t sc_bpf;              /* BPF data */
54 };
```
if_slvar.h

Figure 3.28 `sl_softc` structure.

43–54 As with all interface structures, `sl_softc` starts with an `ifnet` structure followed by device-specific information.

In addition to the output queue found in the `ifnet` structure, a SLIP device maintains a separate queue, `sc_fastq`, for packets requesting low-delay service—typically generated by interactive applications.

`sc_ttyp` points to the associated terminal device. The two pointers `sc_buf` and `sc_ep` point to the first and last bytes of the buffer for an incoming SLIP packet. `sc_mp` points to the location for the next incoming byte and is advanced as additional bytes arrive.

The four flags defined by the SLIP driver are shown in Figure 3.29.

Constant	`sc_softc` member	Description
`SC_COMPRESS`	`sc_if.if_flags`	`IFF_LINK0`; compress TCP traffic
`SC_NOICMP`	`sc_if.if_flags`	`IFF_LINK1`; suppress ICMP traffic
`SC_AUTOCOMP`	`sc_if.if_flags`	`IFF_LINK2`; auto-enable TCP compression
`SC_ERROR`	`sc_flags`	error detected; discard incoming frame

Figure 3.29 SLIP `if_flags` and `sc_flags` values.

SLIP defines the three interface flags reserved for the device driver in the `ifnet` structure and one additional flag defined in the `sl_softc` structure.

`sc_escape` is used by the IP encapsulation mechanism for serial lines (Section 5.3), while TCP header compression (Section 29.13) information is kept in `sc_comp`.

The BPF information for the SLIP device is pointed to by `sc_bpf`.

The `sl_softc` structure is initialized by `slattach`, shown in Figure 3.30.

135–152 Unlike `leattach`, which initializes only one interface at a time, the kernel calls `slattach` once and `slattach` initializes all the SLIP interfaces. Hardware devices are initialized as they are discovered by the kernel during `cpu_startup`, while pseudo-devices are initialized all at once when `main` calls the `pdev_attach` function for the device. `if_mtu` for a SLIP device is 296 bytes (`SLMTU`). This accommodates the

if_sl.c

```
135 void
136 slattach()
137 {
138     struct sl_softc *sc;
139     int     i = 0;

140     for (sc = sl_softc; i < NSL; sc++) {
141         sc->sc_if.if_name = "sl";
142         sc->sc_if.if_next = NULL;
143         sc->sc_if.if_unit = i++;
144         sc->sc_if.if_mtu = SLMTU;
145         sc->sc_if.if_flags =
146             IFF_POINTOPOINT | SC_AUTOCOMP | IFF_MULTICAST;
147         sc->sc_if.if_type = IFT_SLIP;
148         sc->sc_if.if_ioctl = slioctl;
149         sc->sc_if.if_output = sloutput;
150         sc->sc_if.if_snd.ifq_maxlen = 50;
151         sc->sc_fastq.ifq_maxlen = 32;
152         if_attach(&sc->sc_if);
153         bpfattach(&sc->sc_bpf, &sc->sc_if, DLT_SLIP, SLIP_HDRLEN);
154     }
155 }
```

if_sl.c

Figure 3.30 `slattach` function.

standard 20-byte IP header, the standard 20-byte TCP header, and 256 bytes of user data (Section 5.3).

A SLIP network consists of two interfaces at each end of a serial communication line. `slattach` turns on `IFF_POINTOPOINT`, `SC_AUTOCOMP`, and `IFF_MULTICAST` in `if_flags`.

The SLIP interface limits the length of its output packet queue, `if_snd`, to 50 and its own internal queue, `sc_fastq`, to 32. Figure 3.42 shows that the length of the `if_snd` queue defaults to 50 (`ifqmaxlen`) if the driver selects a length, so the initialization here is redundant.

The Ethernet driver doesn't set its output queue length explicitly and relies on `ifinit` (Figure 3.42) to set it to the system default.

`if_attach` expects a pointer to an `ifnet` structure so `slattach` passes the address of `sc_if`, an `ifnet` structure and the first member of the `sl_softc` structure.

A special program, `slattach`, is run (from the `/etc/netstart` initialization file) after the kernel has been initialized and joins the SLIP interface and an asynchronous serial device by opening the serial device and issuing `ioctl` commands (Section 5.3).

153–155 For each SLIP device, `slattach` calls `bpfattach` to register the interface with BPF.

3.10 Loopback Initialization

Finally, we show the initialization for the single loopback interface. The loopback interface places any outgoing packets back on an appropriate input queue. There is no hardware device associated with the interface. The loopback pseudo-device is initialized when `main` calls `loopattach` indirectly through the `pdev_attach` pointer in the loopback's `pdevinit` structure. Figure 3.31 shows the `loopattach` function.

if_loop.c

```
41 void
42 loopattach(n)
43 int     n;
44 {
45     struct ifnet *ifp = &loif;

46     ifp->if_name = "lo";
47     ifp->if_mtu = LOMTU;
48     ifp->if_flags = IFF_LOOPBACK | IFF_MULTICAST;
49     ifp->if_ioctl = loioctl;
50     ifp->if_output = looutput;
51     ifp->if_type = IFT_LOOP;
52     ifp->if_hdrlen = 0;
53     ifp->if_addrlen = 0;
54     if_attach(ifp);
55     bpfattach(&ifp->if_bpf, ifp, DLT_NULL, sizeof(u_int));
56 }
```

if_loop.c

Figure 3.31 Loopback interface initialization.

41–56 The loopback `if_mtu` is set to 1536 bytes (`LOMTU`). In `if_flags`, `IFF_LOOPBACK` and `IFF_MULTICAST` are set. A loopback interface has no link header or hardware address, so `if_hdrlen` and `if_addrlen` are set to 0. `if_attach` finishes the initialization of the `ifnet` structure and `bpfattach` registers the loopback interface with BPF.

The loopback MTU should be at least 1576 ($40 + 3 \times 512$) to leave room for a standard TCP/IP header. Solaris 2.3, for example, sets the loopback MTU to 8232 ($40 + 8 \times 1024$). These calculations are biased toward the Internet protocols; other protocols may have default headers larger than 40 bytes.

3.11 `if_attach` Function

The three interface initialization functions shown earlier each call `if_attach` to complete initialization of the interface's `ifnet` structure and to insert the structure on the list of previously configured interfaces. Also, in `if_attach`, the kernel initializes and assigns each interface a link-level address. Figure 3.32 illustrates the data structures constructed by `if_attach`.

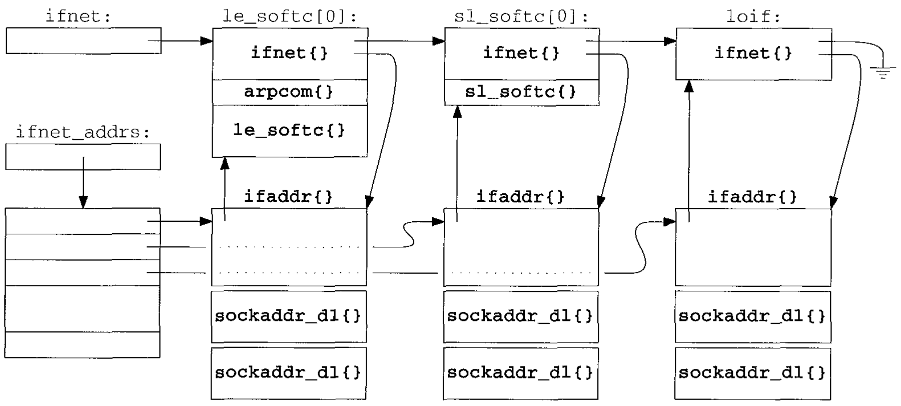


Figure 3.32 ifnet list.

In Figure 3.32, if_attach has been called three times: from leattach with an le_softc structure, from slattach with an sl_softc structure, and from loopattach with a generic ifnet structure. Each time it is called it adds another ifnet structure to the ifnet list, creates a link-level ifaddr structure for the interface (which contains two sockaddr_dl structures, Figure 3.33), and initializes an entry in the ifnet_addrs array.

The structures contained within le_softc[0] and sl_softc[0] are nested as shown in Figure 3.20.

After this initialization, the interfaces are configured only with link-level addresses. IP addresses, for example, are not configured until much later by the ifconfig program (Section 6.6).

The link-level address contains a logical address for the interface and a hardware address if supported by the network (e.g., a 48-bit Ethernet address for le0). The hardware address is used by ARP and the OSI protocols, while the logical address within a sockaddr_dl contains a name and numeric index for the interface within the kernel, which supports a table lookup for converting between an interface index and the associated ifaddr structure (ifa_ifwithnet, Figure 6.32).

The sockaddr_dl structure is shown in Figure 3.33.

55–57 Recall from Figure 3.18 that sdl_len specifies the length of the entire address and sdl_family specifies the address family, in this case AF_LINK.

58 sdl_index identifies the interface within the kernel. In Figure 3.32 the Ethernet interface would have an index of 1, the SLIP interface an index of 2, and the loopback interface an index of 3. The global integer if_index contains the last index assigned by the kernel.

60 sdl_type is initialized from the if_type member of the ifnet structure associated with this datalink address.

```
                                                                        if_dl.h
55 struct sockaddr_dl {
56     u_char  sdl_len;           /* Total length of sockaddr */
57     u_char  sdl_family;        /* AF_LINK */
58     u_short sdl_index;         /* if != 0, system given index for
59                                   interface */
60     u_char  sdl_type;          /* interface type (Figure 3.9) */
61     u_char  sdl_nlen;          /* interface name length, no trailing 0
62                                   reqd. */
63     u_char  sdl_alen;          /* link level address length */
64     u_char  sdl_slen;          /* link layer selector length */
65     char    sdl_data[12];      /* minimum work area, can be larger;
66                                   contains both if name and ll address */
67 };

68 #define LLADDR(s) ((caddr_t)((s)->sdl_data + (s)->sdl_nlen))
                                                                        if_dl.h
```

Figure 3.33 sockaddr_dl structure.

61–68 In addition to a numeric index, each interface has a text name formed from the if_name and if_unit members of the ifnet structure. For example, the first SLIP interface is called "sl0" and the second is called "sl1". The text name is stored at the front of the sdl_data array, and sdl_nlen is the length of this name in bytes (3 in our SLIP example).

The datalink address is also stored in the structure. The macro LLADDR converts a pointer into a sockaddr_dl structure to a pointer to the first byte beyond the text name. sdl_alen is the length of the hardware address. For an Ethernet device, the 48-bit hardware address appears in the sockaddr_dl structure beyond the text name. Figure 3.38 shows an initialized sockaddr_dl structure.

Net/3 does not use sdl_slen.

if_attach updates two global variables. The first, if_index, holds the index of the last interface in the system and the second, ifnet_addrs, points to an array of ifaddr pointers. Each entry in the array points to the link-level address of an interface. The array provides quick access to the link-level address for every interface in the system.

The if_attach function is long and consists of several tricky assignment statements. We describe it in four parts, starting with Figure 3.34.

59–74 if_attach has a single argument, ifp, a pointer to the ifnet structure that has been initialized by a network device driver. Net/3 keeps all the ifnet structures on a linked list headed by the global pointer ifnet. The while loop locates the end of the list and saves the address of the null pointer at the end of the list in p. After the loop, the new ifnet structure is attached to the end of the ifnet list, if_index is incremented, and the new index is assigned to ifp->if_index.

Resize ifnet_addrs array if necessary

75–85 The first time through if_attach, the ifnet_addrs array doesn't exist so space for 16 entries ($16 = 8 \ll 1$) is allocated. When the array becomes full, a new array of twice the size is allocated and the entries from the old array are copied to the new array.

if.c
```
void
if_attach(ifp)
struct ifnet *ifp;
{
    unsigned socksize, ifasize;
    int     namelen, unitlen, masklen, ether_output();
    char    workbuf[12], *unitname;
    struct ifnet **p = &ifnet;  /* head of interface list */
    struct sockaddr_dl *sdl;
    struct ifaddr *ifa;
    static int if_indexlim = 8; /* size of ifnet_addrs array */
    extern void link_rtrequest();

    while (*p)                  /* find end of interface list */
        p = &((*p)->if_next);
    *p = ifp;
    ifp->if_index = ++if_index; /* assign next index */

    /* resize ifnet_addrs array if necessary */
    if (ifnet_addrs == 0 || if_index >= if_indexlim) {
        unsigned n = (if_indexlim <<= 1) * sizeof(ifa);
        struct ifaddr **q = (struct ifaddr **)
                    malloc(n, M_IFADDR, M_WAITOK);

        if (ifnet_addrs) {
            bcopy((caddr_t) ifnet_addrs, (caddr_t) q, n / 2);
            free((caddr_t) ifnet_addrs, M_IFADDR);
        }
        ifnet_addrs = q;
    }
```
if.c

Figure 3.34 `if_attach` function: assign interface index.

> `if_indexlim` is a static variable private to `if_attach`. `if_indexlim` is updated by the `<<=` operator.

The `malloc` and `free` functions in Figure 3.34 are *not* the standard C library functions of the same name. The second argument in the kernel versions specifies a type, which is used by optional diagnostic code in the kernel to detect programming errors. If the third argument to `malloc` is `M_WAITOK`, the function blocks the calling process if it needs to wait for free memory to become available. If the third argument is `M_DONTWAIT`, the function does not block and returns a null pointer when no memory is available.

The next section of `if_attach`, shown in Figure 3.35, prepares a text name for the interface and computes the size of the link-level address.

Create link-level name and compute size of link-level address

86–99 `if_attach` constructs the name of the interface from `if_unit` and `if_name`. The function `sprint_d` converts the numeric value of `if_unit` to a string stored in `workbuf`. `masklen` is the number of bytes occupied by the information before `sdl_data` in the `sockaddr_dl` array plus the size of the text name for the interface

if.c
```
    /* create a Link Level name for this device */
    unitname = sprint_d((u_int) ifp->if_unit, workbuf, sizeof(workbuf));
    namelen = strlen(ifp->if_name);
    unitlen = strlen(unitname);

    /* compute size of sockaddr_dl structure for this device */
#define _offsetof(t, m) ((int)((caddr_t)&((t *)0)->m))
    masklen = _offsetof(struct sockaddr_dl, sdl_data[0]) +
            unitlen + namelen;
    socksize = masklen + ifp->if_addrlen;
#define ROUNDUP(a) (1 + (((a) - 1) | (sizeof(long) - 1)))
    socksize = ROUNDUP(socksize);
    if (socksize < sizeof(*sdl))
        socksize = sizeof(*sdl);
    ifasize = sizeof(*ifa) + 2 * socksize;
```
if.c

Figure 3.35 `if_attach` function: compute size of link-level address.

(`namelen + unitlen`). The function rounds `socksize`, which is `masklen` plus the hardware address length (`if_addrlen`), up to the boundary of a long integer (`ROUNDUP`). If this is less than the size of a `sockaddr_dl` structure, the standard `sockaddr_dl` structure is used. `ifasize` is the size of an `ifaddr` structure plus two times `socksize`, so it can hold the `sockaddr_dl` structures.

In the next section, `if_attach` allocates and links the structures together, as shown in Figure 3.36.

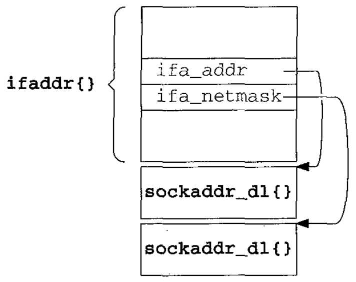


Figure 3.36 The link-level address and mask assigned during `if_attach`.

In Figure 3.36 there is a gap between the `ifaddr` structure and the two `sockaddr_dl` structures to illustrate that they are allocated in a contiguous area of memory but that they are not defined by a single C structure.

The organization shown in Figure 3.36 is repeated in the `in_ifaddr` structure; the pointers in the generic `ifaddr` portion of the structure point to specialized `sockaddr` structures allocated in the device-specific portion of the structure, in this case, `sockaddr_dl` structures. Figure 3.37 shows the initialization of these structures.

if.c

```
100     if (ifa = (struct ifaddr *) malloc(ifasize, M_IFADDR, M_WAITOK)) {
101         bzero((caddr_t) ifa, ifasize);

102         /* First: initialize the sockaddr_dl address */
103         sdl = (struct sockaddr_dl *) (ifa + 1);
104         sdl->sdl_len = socksize;
105         sdl->sdl_family = AF_LINK;
106         bcopy(ifp->if_name, sdl->sdl_data, namelen);
107         bcopy(unitname, namelen + (caddr_t) sdl->sdl_data, unitlen);
108         sdl->sdl_nlen = (namelen += unitlen);
109         sdl->sdl_index = ifp->if_index;
110         sdl->sdl_type = ifp->if_type;
111         ifnet_addrs[if_index - 1] = ifa;
112         ifa->ifa_ifp = ifp;
113         ifa->ifa_next = ifp->if_addrlist;
114         ifa->ifa_rtrequest = link_rtrequest;
115         ifp->if_addrlist = ifa;
116         ifa->ifa_addr = (struct sockaddr *) sdl;

117         /* Second: initialize the sockaddr_dl mask */
118         sdl = (struct sockaddr_dl *) (socksize + (caddr_t) sdl);
119         ifa->ifa_netmask = (struct sockaddr *) sdl;
120         sdl->sdl_len = masklen;
121         while (namelen != 0)
122             sdl->sdl_data[--namelen] = 0xff;
123     }
```

if.c

Figure 3.37 `if_attach` function: allocate and initialize link-level address.

The address

100–116 If enough memory is available, `bzero` fills the new structure with 0s and `sdl` points to the first `sockaddr_dl` just after the `ifnet` structure. If no memory is available, the code is skipped.

`sdl_len` is set to the length of the `sockaddr_dl` structure, and `sdl_family` is set to `AF_LINK`. A text name is constructed within `sdl_data` from `if_name` and `unitname`, and the length is saved in `sdl_nlen`. The interface's index is copied into `sdl_index` as well as the interface type into `sdl_type`. The allocated structure is inserted into the `ifnet_addrs` array and linked to the `ifnet` structure by `ifa_ifp` and `ifa_addrlist`. Finally, the `sockaddr_dl` structure is connected to the `ifnet` structure with `ifa_addr`. Ethernet interfaces replace the default function, `link_rtrequest` with `arp_rtrequest`. The loopback interface installs `loop_rtrequest`. We describe `ifa_rtrequest` and `arp_rtrequest` in Chapters 19 and 21. `link_rtrequest` and `loop_rtrequest` are left for readers to investigate on their own. This completes the initialization of the first `sockaddr_dl` structure.

The mask

117–123 The second `sockaddr_dl` structure is a bit mask that selects the text name that appears in the first structure. `ifa_netmask` from the `ifaddr` structure points to the mask structure (which in this case selects the interface text name and not a network mask). The `while` loop turns on the bits in the bytes corresponding to the name.

Figure 3.38 shows the two initialized sockaddr_dl structures for our example Ethernet interface, where if_name is "le", if_unit is 0, and if_index is 1.

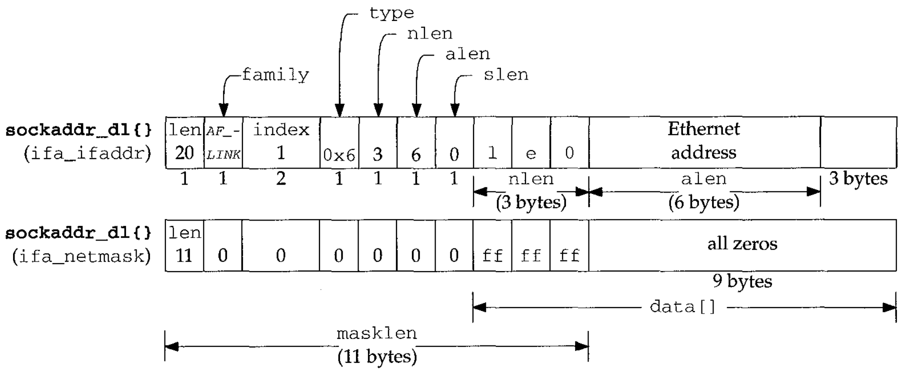


Figure 3.38 The initialized Ethernet sockaddr_dl structures (sdl_ prefix omitted).

In Figure 3.38, the address is shown after ether_ifattach has done additional initialization of the structure (Figure 3.41).

Figure 3.39 shows the structures after the first interface has been attached by if_attach.

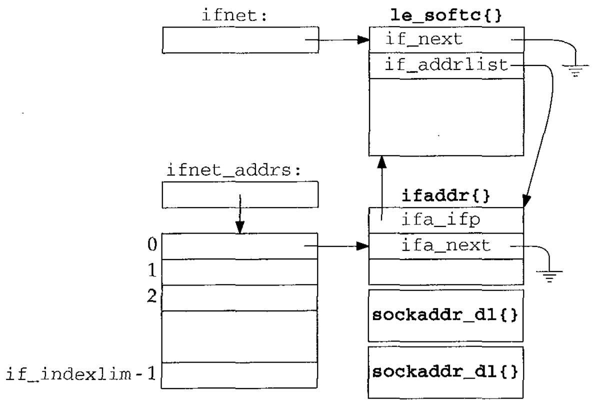


Figure 3.39 The ifnet and sockaddr_dl structures after if_attach is called for the first time.

At the end of if_attach, the ether_ifattach function is called for Ethernet devices, as shown in Figure 3.40.

124–127 ether_ifattach isn't called earlier (from leattach, for example) because it copies the Ethernet hardware address into the sockaddr_dl allocated by if_attach.

The XXX comment indicates that the author found it easier to insert the code here once than to modify all the Ethernet drivers.

if.c

```
    /* XXX -- Temporary fix before changing 10 ethernet drivers */
    if (ifp->if_output == ether_output)
        ether_ifattach(ifp);
}
```

if.c

Figure 3.40 `if_attach` function: Ethernet initialization.

`ether_ifattach` function

The `ether_ifattach` function performs the `ifnet` structure initialization common to all Ethernet devices.

if_ethersubr.c

```
338 void
339 ether_ifattach(ifp)
340 struct ifnet *ifp;
341 {
342     struct ifaddr *ifa;
343     struct sockaddr_dl *sdl;

344     ifp->if_type = IFT_ETHER;
345     ifp->if_addrlen = 6;
346     ifp->if_hdrlen = 14;
347     ifp->if_mtu = ETHERMTU;
348     for (ifa = ifp->if_addrlist; ifa; ifa = ifa->ifa_next)
349         if ((sdl = (struct sockaddr_dl *) ifa->ifa_addr) &&
350             sdl->sdl_family == AF_LINK) {
351             sdl->sdl_type = IFT_ETHER;
352             sdl->sdl_alen = ifp->if_addrlen;
353             bcopy((caddr_t) ((struct arpcom *) ifp)->ac_enaddr,
354                   LLADDR(sdl), ifp->if_addrlen);
355             break;
356         }
357 }
```

if_ethersubr.c

Figure 3.41 `ether_ifattach` function.

338–357 For an Ethernet device, `if_type` is `IFT_ETHER`, the hardware address is 6 bytes long, the entire Ethernet header is 14 bytes in length, and the Ethernet MTU is 1500 (`ETHERMTU`).

The MTU was already assigned by `leattach`, but other Ethernet device drivers may not have performed this initialization.

Section 4.3 discusses the Ethernet frame organization in more detail. The `for` loop locates the link-level address for the interface and then initializes the Ethernet hardware address information in the `sockaddr_dl` structure. The Ethernet address that was copied into the `arpcom` structure during system initialization is now copied into the link-level address.

3.12 `ifinit` Function

After the interface structures are initialized and linked together, `main` (Figure 3.23) calls `ifinit`, shown in Figure 3.42.

if.c
```
43 void
44 ifinit()
45 {
46     struct ifnet *ifp;

47     for (ifp = ifnet; ifp; ifp = ifp->if_next)
48         if (ifp->if_snd.ifq_maxlen == 0)
49             ifp->if_snd.ifq_maxlen = ifqmaxlen;     /* set default length */
50     if_slowtimo(0);
51 }
```
if.c

Figure 3.42 `ifinit` function.

43–51 The `for` loop traverses the interface list and sets the maximum size of each interface output queue to 50 (`ifqmaxlen`) if it hasn't already been set by the interface's attach function.

An important consideration for the size of the output queue is the number of packets required to send a maximum-sized datagram. For Ethernet, if a process calls `sendto` with 65,507 bytes of data, it is fragmented into 45 fragments and each fragment is put onto the interface output queue. If the queue were much smaller, the process could never send that large a datagram, as the queue wouldn't have room.

`if_slowtimo` starts the interface watchdog timers. When an interface timer expires, the kernel calls the watchdog function for the interface. An interface can reset the timer periodically to prevent the watchdog function from being called, or set `if_timer` to 0 if the watchdog function is not needed. Figure 3.43 shows the `if_slowtimo` function.

if.c
```
void
if_slowtimo(arg)
void   *arg;
{
    struct ifnet *ifp;
    int     s = splimp();

    for (ifp = ifnet; ifp; ifp = ifp->if_next) {
        if (ifp->if_timer == 0 || --ifp->if_timer)
            continue;
        if (ifp->if_watchdog)
            (*ifp->if_watchdog) (ifp->if_unit);
    }
    splx(s);
    timeout(if_slowtimo, (void *) 0, hz / IFNET_SLOWHZ);
}
```
if.c

Figure 3.43 `if_slowtimo` function.

338–343 The single argument, arg, is not used but is required by the prototype for the slow timeout functions (Section 7.4).

344–352 if_slowtimo ignores interfaces with if_timer equal to 0; if if_timer does not equal 0, if_slowtimo decrements if_timer and calls the if_watchdog function associated with the interface when the timer reaches 0. Packet processing is blocked by splimp during if_slowtimo. Before returning, ip_slowtimo calls timeout to schedule a call to itself in hz/IFNET_SLOWHZ clock ticks. hz is the number of clock ticks that occur in 1 second (often 100). It is set at system initialization and remains constant thereafter. Since IFNET_SLOWHZ is defined to be 1, the kernel calls if_slowtimo once every hz clock ticks, which is once per second.

The functions scheduled by the timeout function are called back by the kernel's callout function. See [Leffler et al. 1989] for additional details.

3.13 Summary

In this chapter we have examined the ifnet and ifaddr structures that are allocated for each network interface found at system initialization time. The ifnet structures are linked into the ifnet list. The link-level address for each interface is initialized, attached to the ifnet structure's address list, and entered into the if_addrs array.

We discussed the generic sockaddr structure and its sa_family, and sa_len members, which specify the type and length of every address. We also looked at the initialization of the sockaddr_dl structure for a link-level address.

In this chapter, we introduced the three example network interfaces that we use throughout the book.

Exercises

3.1 The netstat program on many Unix systems lists network interfaces and their configuration. Try netstat -i on a system you have access to. What are the names (if_name) and maximum transmission units (if_mtu) of the network interfaces?

3.2 In if_slowtimo (Figure 3.43) the splimp and splx calls appear outside the loop. What are the advantages and disadvantages of this arrangement compared with placing the calls within the loop?

3.3 Why is SLIP's interactive queue shorter than SLIP's standard output queue?

3.4 Why aren't if_hdrlen and if_addrlen initialized in slattach?

3.5 Draw a picture similar to Figure 3.38 for the SLIP and loopback devices.

4

Interfaces: Ethernet

4.1 Introduction

In Chapter 3 we discussed the data structures used by all interfaces and the initialization of those data structures. In this chapter we show how the Ethernet device driver operates once it has been initialized and is receiving and transmitting frames. The second half of this chapter covers the generic `ioctl` commands for configuring network devices. Chapter 5 covers the SLIP and loopback drivers.

We won't go through the entire source code for the Ethernet driver, since it is around 1,000 lines of C code (half of which is concerned with the hardware details of one particular interface card), but we do look at the device-independent Ethernet code and how the driver interfaces with the rest of the kernel.

If the reader is interested in going through the source code for a driver, the Net/3 release contains the source code for many different interfaces. Access to the interface's technical specifications is required to understand the device-specific commands. Figure 4.1 shows the various drivers provided with Net/3, including the LANCE driver, which we discuss in this text.

Network device drivers are accessed through the seven function pointers in the `ifnet` structure (Figure 3.6). Figure 4.2 lists the entry points to our three example drivers.

Input functions are not included in Figure 4.2 as they are interrupt-driven for network devices. The configuration of interrupt service routines is hardware-dependent and beyond the scope of this book. We'll identify the functions that handle device interrupts, but not the mechanism by which these functions are invoked.

Device	File
DEC DEUNA Interface	vax/if/if_de.c
3Com Ethernet Interface	vax/if/if_ec.c
Excelan EXOS 204 Interface	vax/if/if_ex.c
Interlan Ethernet Communications Controller	vax/if/if_il.c
Interlan NP100 Ethernet Communications Controller	vax/if/if_ix.c
Digital Q-BUS to NI Adapter	vax/if/if_qe.c
CMC ENP-20 Ethernet Controller	tahoe/if/if_enp.c
Excelan EXOS 202(VME) & 203(QBUS)	tahoe/if/if_ex.c
ACC VERSAbus Ethernet Controller	tahoe/if/if_ace.c
AMD 7990 LANCE Interface	**hp300/dev/if_le.c**
NE2000 Ethernet	i386/isa/if_ne.c
Western Digital 8003 Ethernet Adapter	i386/isa/if_we.c

Figure 4.1 Ethernet drivers available in Net/3.

ifnet	Ethernet	SLIP	Loopback	Description
if_init	leinit			hardware initialization
if_output	ether_output	sloutput	looutput	accept and queue frame for transmission
if_start	lestart			begin transmission of frame
if_done				output complete (unused)
if_ioctl	leioctl	slioctl	loioctl	handle ioctl commands from a process
if_reset	lereset			reset the device to a known state
if_watchdog				watch the device for failures or collect statistics

Figure 4.2 Interface functions for the example drivers.

Only the if_output and if_ioctl functions are called with any consistency. if_init, if_done, and if_reset are never called or only called from device-specific code (e.g., leinit is called directly by leioctl). if_start is called only by the ether_output function.

4.2 Code Introduction

The code for the Ethernet device driver and the generic interface ioctls resides in two headers and three C files, which are listed in Figure 4.3.

File	Description
netinet/if_ether.h	Ethernet structures
net/if.h	ioctl command definitions
net/if_ethersubr.c	generic Ethernet functions
hp300/dev/if_le.c	LANCE Ethernet driver
net/if.c	ioctl processing

Figure 4.3 Files discussed in this chapter.

Global Variables

The global variables shown in Figure 4.4 include the protocol input queues, the LANCE interface structure, and the Ethernet broadcast address.

Variable	Datatype	Description
arpintrq	struct ifqueue	ARP input queue
clnlintrq	struct ifqueue	CLNP input queue
ipintrq	struct ifqueue	IP input queue
le_softc	struct le_softc []	LANCE Ethernet interface
etherbroadcastaddr	u_char []	Ethernet broadcast address

Figure 4.4 Global variables introduced in this chapter.

le_softc is an array, since there can be several Ethernet interfaces.

Statistics

The statistics collected in the ifnet structure for each interface are described in Figure 4.5.

ifnet member	Description	Used by SNMP
if_collisions	#collisions on CSMA interfaces	
if_ibytes	total #bytes received	•
if_ierrors	#packets received with input errors	•
if_imcasts	#packets received as multicasts	•
if_ipackets	#packets received on interface	•
if_iqdrops	#packets dropped on input, by this interface	•
if_lastchange	time of last change to statistics	•
if_noproto	#packets destined for unsupported protocol	•
if_obytes	total #bytes sent	•
if_oerrors	#output errors on interface	•
if_omcasts	#packets sent as multicasts	•
if_opackets	#packets sent on interface	•
if_snd.ifq_drops	#packets dropped during output	•
if_snd.ifq_len	#packets in output queue	

Figure 4.5 Statistics maintained in the ifnet structure.

Figure 4.6 shows some sample output from the netstat command, which includes statistics from the ifnet structure.

The first column contains if_name and if_unit displayed as a string. If the interface is shut down (IFF_UP is not set), an asterisk appears next to the name. In Figure 4.6, sl0, sl2, and sl3 are shut down.

The second column shows if_mtu. The output under the "Network" and "Address" headings depends on the type of address. For link-level addresses, the contents of sdl_data from the sockaddr_dl structure are displayed. For IP addresses,

```
                              netstat -i output
Name  Mtu   Network      Address              Ipkts Ierrs    Opkts Oerrs   Coll
le0   1500  <Link>8.0.9.13.d.33            28680519   814 29234729    12 942798
le0   1500  128.32.33    128.32.33.5       28680519   814 29234729    12 942798
sl0*  296   <Link>                            54036     0    45402     0      0
sl0*  296   128.32.33    128.32.33.5          54036     0    45402     0      0
sl1   296   <Link>                            40397     0    33544     0      0
sl1   296   128.32.33    128.32.33.5          40397     0    33544     0      0
sl2*  296   <Link>                                0     0        0     0      0
sl3*  296   <Link>                                0     0        0     0      0
lo0   1536  <Link>                           493599     0   493599     0      0
lo0   1536  127          127.0.0.1           493599     0   493599     0      0
```

Figure 4.6 Sample interface statistics.

the subnet and unicast addresses are displayed. The remaining columns are `if_ipackets`, `if_ierrors`, `if_opackets`, `if_oerrors`, and `if_collisions`.

- Approximately 3% of the packets collide on output (942,798/29,234,729 = 3%).
- The SLIP output queues are never full on this machine since there are no output errors for the SLIP interfaces.
- The 12 Ethernet output errors are problems detected by the LANCE hardware during transmission. Some of these errors may also be counted as collisions.
- The 814 Ethernet input errors are also problems detected by the hardware, such as packets that are too short or that have invalid checksums.

SNMP Variables

Figure 4.7 shows a single interface entry object (`ifEntry`) from the SNMP interface table (`ifTable`), which is constructed from the `ifnet` structures for each interface.

The ISODE SNMP agent derives `ifSpeed` from `if_type` and maintains an internal variable for `ifAdminStatus`. The agent reports `ifLastChange` based on `if_lastchange` in the `ifnet` structure but relative to the agent's boot time, not the boot time of the system. The agent returns a null variable for `ifSpecific`.

4.3 Ethernet Interface

Net/3 Ethernet device drivers all follow the same general design. This is common for most Unix device drivers because the writer of a driver for a new interface card often starts with a working driver for another card and modifies it. In this section we'll provide a brief overview of the Ethernet standard and outline the design of an Ethernet driver. We'll refer to the LANCE driver to illustrate the design.

Figure 4.8 illustrates Ethernet encapsulation of an IP packet.

Interface table, index = < *ifIndex* >		
SNMP variable	`ifnet` member	Description
`ifIndex`	`if_index`	uniquely identifies the interface
`ifDescr`	`if_name`	text name of interface
`ifType`	`if_type`	type of interface (e.g., Ethernet, SLIP, etc.)
`ifMtu`	`if_mtu`	MTU of the interface in bytes
`ifSpeed`	(see text)	nominal speed of the interface in bits per second
`ifPhysAddress`	`ac_enaddr`	media address (from `arpcom` structure)
`ifAdminStatus`	(see text)	desired state of the interface (`IFF_UP` flag)
`ifOperStatus`	`if_flags`	operational state of the interface (`IFF_UP` flag)
`ifLastChange`	(see text)	last time the statistics changed
`ifInOctets`	`if_ibytes`	total #input bytes
`ifInUcastPkts`	`if_ipackets - if_imcasts`	#input unicast packets
`ifInNUcastPkts`	`if_imcasts`	#input broadcast or multicast packets
`ifInDiscards`	`if_iqdrops`	#packets discarded because of implementation limits
`ifInErrors`	`if_ierrors`	#packets with errors
`ifInUnknownProtos`	`if_noproto`	#packets destined to an unknown protocol
`ifOutOctets`	`if_obytes`	#output bytes
`ifOutUcastPkts`	`if_opackets - if_omcasts`	#output unicast packets
`ifOutNUcastPkts`	`if_omcasts`	#output broadcast or multicast packets
`ifOutDiscards`	`if_snd.ifq_drops`	#output packets dropped because of implementation limits
`ifOutErrors`	`if_oerrors`	#output packets dropped because of errors
`ifOutQLen`	`if_snd.ifq_len`	output queue length
`ifSpecific`	n/a	SNMP object ID for media-specific information (not implemented)

Figure 4.7 Variables in interface table: `ifTable`.

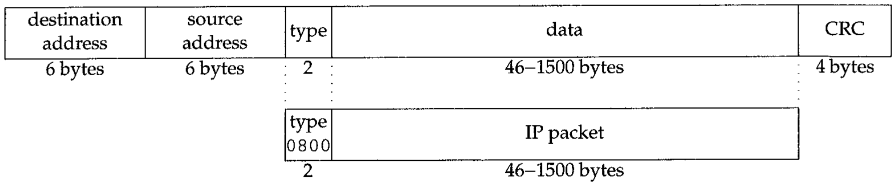


Figure 4.8 Ethernet encapsulation of an IP packet.

Ethernet frames consist of 48-bit destination and source addresses followed by a 16-bit type field that identifies the format of the data carried by the frame. For IP packets, the type is `0x0800` (2048). The frame is terminated with a 32-bit CRC (cyclic redundancy check), which detects errors in the frame.

We are describing the original Ethernet framing standard published in 1982 by Digital Equipment Corp., Intel Corp., and Xerox Corp., as it is the most common form used today in TCP/IP networks. An alternative form is specified by the IEEE (Institute of Electrical and Electronics Engineers) 802.2 and 802.3 standards. Section 2.2 in Volume 1 describes the differences between the two forms. See [Stallings 1987] for more information on the IEEE standards.

Encapsulation of IP packets for Ethernet is specified by RFC 894 [Hornig 1984] and for 802.3 networks by RFC 1042 [Postel and Reynolds 1988].

We will refer to the 48-bit Ethernet addresses as *hardware addresses*. The translation from IP to hardware addresses is done by the ARP protocol described in Chapter 21 (RFC 826 [Plummer 1982]) and from hardware to IP addresses by the RARP protocol (RFC 903 [Finlayson et al. 1984]). Ethernet addresses come in two types, *unicast* and *multicast*. A unicast address specifies a single Ethernet interface, and a multicast address specifies a group of Ethernet interfaces. An Ethernet *broadcast* is a multicast received by all interfaces. Ethernet unicast addresses are assigned by the device's manufacturer, although some devices allow the address to be changed by software.

Some DECNET protocols require the hardware addresses of a multihomed host to be identical, so DECNET must be able to change the Ethernet unicast address of a device.

Figure 4.9 illustrates the data structures and functions that are part of the Ethernet interface.

In figures, a function is identified by an ellipse (`leintr`), data structures by a box (`le_softc[0]`), `le_softc` and a group of functions by a rounded box (ARP protocol).

In the top left corner of Figure 4.9 we show the input queues for the OSI Connectionless Network Layer (`clnl`) protocol, IP, and ARP. We won't say anything more about `clnlintrq`, but include it to emphasize that `ether_input` demultiplexes Ethernet frames into multiple protocol queues.

Technically, OSI uses the term Connectionless Network *Protocol* (CLNP versus CLNL) but we show the terminology used by the Net/3 code. The official standard for CLNP is ISO 8473. [Stallings 1993] summarizes the standard.

The `le_softc` interface structure is in the center of Figure 4.9. We are interested only in the `ifnet` and `arpcom` portions of the structure. The remaining portions are specific to the LANCE hardware. We showed the `ifnet` structure in Figure 3.6 and the `arpcom` structure in Figure 3.26.

`leintr` Function

We start with the reception of Ethernet frames. For now, we assume that the hardware has been initialized and the system has been configured so that `leintr` is called when the interface generates an interrupt. In normal operation, an Ethernet interface receives frames destined for its unicast hardware address and for the Ethernet broadcast address. When a complete frame is available, the interface generates an interrupt and the kernel calls `leintr`.

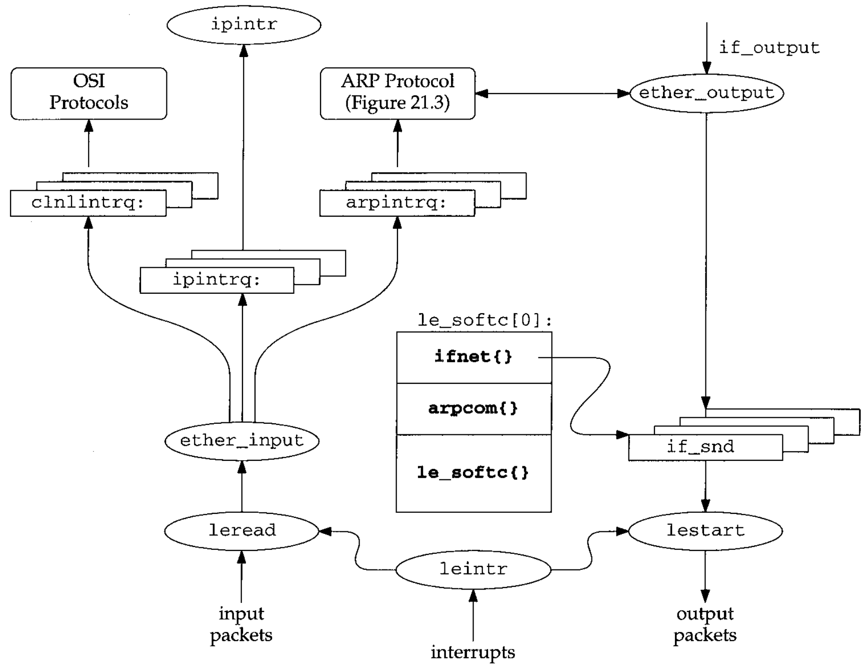


Figure 4.9 Ethernet device driver.

In Chapter 12, we'll see that many Ethernet interfaces may be configured to receive Ethernet multicast frames (other than broadcasts).

Some interfaces can be configured to run in *promiscuous mode* in which the interface receives all frames that appear on the network. The tcpdump program described in Volume 1 can take advantage of this feature using BPF.

leintr examines the hardware and, if a frame has arrived, calls leread to transfer the frame from the interface to a chain of mbufs (with m_devget). If the hardware reports that a frame transmission has completed or an error has been detected (such as a bad checksum), leintr updates the appropriate interface statistics, resets the hardware, and calls lestart, which attempts to transmit another frame.

All Ethernet device drivers deliver their received frames to ether_input for further processing. The mbuf chain constructed by the device driver does not include the Ethernet header, so it is passed as a separate argument to ether_input. The ether_header structure is shown in Figure 4.10.

38–42 The Ethernet CRC is not generally available. It is computed and checked by the interface hardware, which discards frames that arrive with an invalid CRC. The Ethernet device driver is responsible for converting ether_type between network and host byte order. Outside of the driver, it is always in host byte order.

if_ether.h

```
struct ether_header {
    u_char  ether_dhost[6];      /* Ethernet destination address */
    u_char  ether_shost[6];      /* Ethernet source address */
    u_short ether_type;          /* Ethernet frame type */
};
```

if_ether.h

Figure 4.10 The `ether_header` structure.

`leread` Function

The `leread` function (Figure 4.11) starts with a contiguous buffer of memory passed to it by `leintr` and constructs an `ether_header` structure and a chain of mbufs. The chain contains the data from the Ethernet frame. `leread` also passes the incoming frame to BPF.

if_le.c

```
leread(unit, buf, len)
int     unit;
char   *buf;
int     len;
{
    struct le_softc *le = &le_softc[unit];
    struct ether_header *et;
    struct mbuf *m;
    int     off, resid, flags;

    le->sc_if.if_ipackets++;
    et = (struct ether_header *) buf;
    et->ether_type = ntohs((u_short) et->ether_type);
    /* adjust input length to account for header and CRC */
    len = len - sizeof(struct ether_header) - 4;
    off = 0;

    if (len <= 0) {
        if (ledebug)
            log(LOG_WARNING,
                "le%d: ierror(runt packet): from %s: len=%d\n",
                unit, ether_sprintf(et->ether_shost), len);
        le->sc_runt++;
        le->sc_if.if_ierrors++;
        return;
    }
    flags = 0;
    if (bcmp((caddr_t) etherbroadcastaddr,
             (caddr_t) et->ether_dhost, sizeof(etherbroadcastaddr)) == 0)
        flags |= M_BCAST;
    if (et->ether_dhost[0] & 1)
        flags |= M_MCAST;

    /*
     * Check if there's a bpf filter listening on this interface.
     * If so, hand off the raw packet to enet.
     */
562     if (le->sc_if.if_bpf) {
563         bpf_tap(le->sc_if.if_bpf, buf, len + sizeof(struct ether_header));

564         /*
565          * Keep the packet if it's a broadcast or has our
566          * physical ethernet address (or if we support
567          * multicast and it's one).
568          */

569         if ((flags & (M_BCAST | M_MCAST)) == 0 &&
570             bcmp(et->ether_dhost, le->sc_addr,
571                  sizeof(et->ether_dhost)) != 0)
572             return;
573     }
574     /*
575      * Pull packet off interface.  Off is nonzero if packet
576      * has trailing header; m_devget will then force this header
577      * information to be at the front, but we still have to drop
578      * the type and length which are at the front of any trailer data.
579      */
580     m = m_devget((char *) (et + 1), len, off, &le->sc_if, 0);
581     if (m == 0)
582         return;
583     m->m_flags |= flags;
584     ether_input(&le->sc_if, et, m);
585 }
```
if_le.c

Figure 4.11 leread function.

528–539 The leintr function passes three arguments to leread: unit, which identifies the particular interface card that received a frame; buf, which points to the received frame; and len, the number of bytes in the frame (including the header and the CRC).

The function constructs the ether_header structure by pointing et to the front of the buffer and converting the Ethernet type value to host byte order.

540–551 The number of data bytes is computed by subtracting the sizes of the Ethernet header and the CRC from len. *Runt packets*, which are too short to be a valid Ethernet frame, are logged, counted, and discarded.

552–557 Next, the destination address is examined to determine if it is the Ethernet broadcast or an Ethernet multicast address. The Ethernet broadcast address is a special case of an Ethernet multicast address; it has every bit set. etherbroadcastaddr is an array defined as

```
u_char  etherbroadcastaddr[6] = { 0xff, 0xff, 0xff, 0xff, 0xff, 0xff };
```

This is a convenient way to define a 48-bit value in C. This technique works only if we assume that characters are 8-bit values—something that isn't guaranteed by ANSI C.

If bcmp reports that etherbroadcastaddr and ether_dhost are the same, the M_BCAST flag is set.

An Ethernet multicast addresses is identified by the low-order bit of the most significant byte of the address. Figure 4.12 illustrates this.

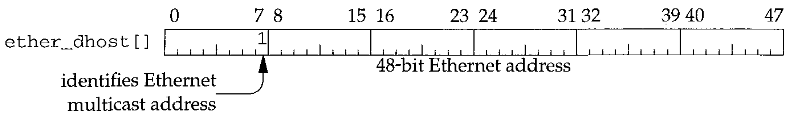


Figure 4.12 Testing for an Ethernet multicast address.

In Chapter 12 we'll see that not all Ethernet multicast frames are IP multicast datagrams and that IP must examine the packet further.

If the multicast bit is on in the address, `M_MCAST` is set in the mbuf header. The order of the tests is important: first `ether_input` compares the entire 48-bit address to the Ethernet broadcast address, and if they are different it checks the low-order bit of the most significant byte to identify an Ethernet multicast address (Exercise 4.1).

558–573 If the interface is tapped by BPF, the frame is passed directly to BPF by calling `bpf_tap`. We'll see that for SLIP and the loopback interfaces, a special BPF frame is constructed since those networks do not have a link-level header (unlike Ethernet).

When an interface is tapped by BPF, it can be configured to run in promiscuous mode and receive all Ethernet frames that appear on the network instead of the subset of frames normally received by the hardware. The packet is discarded by `leread` if it was sent to a unicast address that does not match the interface's address.

574–585 `m_devget` (Section 2.6) copies the data from the buffer passed to `leread` to an mbuf chain it allocates. The first argument to `m_devget` points to the first byte after the Ethernet header, which is the first data byte in the frame. If `m_devget` runs out of memory, `leread` returns immediately. Otherwise the broadcast and multicast flags are set in the first mbuf in the chain, and `ether_input` processes the packet.

`ether_input` Function

`ether_input`, shown in Figure 4.13, examines the `ether_header` structure to determine the type of data that has been received and then queues the received packet for processing.

if_ethersubr.c
```
196 void
197 ether_input(ifp, eh, m)
198 struct ifnet *ifp;
199 struct ether_header *eh;
200 struct mbuf *m;
201 {
202     struct ifqueue *inq;
203     struct llc *l;
204     struct arpcom *ac = (struct arpcom *) ifp;
205     int     s;

206     if ((ifp->if_flags & IFF_UP) == 0) {
207         m_freem(m);
208         return;
209     }
210     ifp->if_lastchange = time;
211     ifp->if_ibytes += m->m_pkthdr.len + sizeof(*eh);
212     if (bcmp((caddr_t) etherbroadcastaddr, (caddr_t) eh->ether_dhost,
213              sizeof(etherbroadcastaddr)) == 0)
214         m->m_flags |= M_BCAST;
215     else if (eh->ether_dhost[0] & 1)
216         m->m_flags |= M_MCAST;
217     if (m->m_flags & (M_BCAST | M_MCAST))
218         ifp->if_imcasts++;

219     switch (eh->ether_type) {
220     case ETHERTYPE_IP:
221         schednetisr(NETISR_IP);
222         inq = &ipintrq;
223         break;

224     case ETHERTYPE_ARP:
225         schednetisr(NETISR_ARP);
226         inq = &arpintrq;
227         break;

228     default:
229         if (eh->ether_type > ETHERMTU) {
230             m_freem(m);
231             return;
232         }

                                        /* OSI code */

307     }

308     s = splimp();
309     if (IF_QFULL(inq)) {
310         IF_DROP(inq);
311         m_freem(m);
312     } else
313         IF_ENQUEUE(inq, m);
314     splx(s);
315 }
```
if_ethersubr.c

Figure 4.13 ether_input function.

Broadcast and multicast recognition

196–209 The arguments to ether_input are ifp, a pointer to the receiving interface's ifnet structure; eh, a pointer to the Ethernet header of the received packet; and m, a pointer to the received packet (excluding the Ethernet header).

Any packets that arrive on an inoperative interface are silently discarded. The interface may not have been configured with a protocol address, or may have been disabled by an explicit request from the ifconfig(8) program (Section 6.6).

210–218 The variable time is a global timeval structure that the kernel maintains with the current time and date, as the number of seconds and microseconds past the Unix Epoch (00:00:00 January 1, 1970, Coordinated Universal Time [UTC]). A brief discussion of

UTC can be found in [Itano and Ramsey 1993]. We'll encounter the `timeval` structure throughout the Net/3 sources:

```
struct timeval {
  long  tv_sec;      /* seconds */
  long  tv_usec;     /* and microseconds */
};
```

`ether_input` updates `if_lastchange` with the current time and increments `if_ibytes` by the size of the incoming packet (the packet length plus the 14-byte Ethernet header).

Next, `ether_input` repeats the tests done by `leread` to determine if the packet is a broadcast or multicast packet.

Some kernels may not have been compiled with the BPF code, so the test must also be done in `ether_input`.

Link-level demultiplexing

219–227 `ether_input` jumps according to the Ethernet type field. For an IP packet, `schednetisr` schedules an IP software interrupt and the IP input queue, `ipintrq`, is selected. For an ARP packet, the ARP software interrupt is scheduled and `arpintrq` is selected.

An *isr* is an interrupt service routine.

In previous BSD releases, ARP packets were processed immediately while at the network interrupt level by calling `arpinput` directly. By queueing the packets, they can be processed at the software interrupt level.

If other Ethernet types are to be handled, a kernel programmer would add additional cases here. Alternately, a process can receive other Ethernet types using BPF. For example, RARP servers are normally implemented using BPF under Net/3.

228–307 The `default` case processes unrecognized Ethernet types or packets that are encapsulated according to the 802.3 standard (such as the OSI connectionless transport). The Ethernet *type* field and the 802.3 *length* field occupy the same position in an Ethernet frame. The two encapsulations can be distinguished because the range of types in an Ethernet encapsulation is distinct from the range of lengths in the 802.3 encapsulation (Figure 4.14). We have omitted the OSI code. [Stallings 1993] contains a description of the OSI link-level protocols.

Range	Description
0 — 1500	IEEE 802.3 *length* field
1501 — 65535	Ethernet *type* field:
2048	IP packet
2054	ARP packet

Figure 4.14 Ethernet *type* and 802.3 *length* fields.

There are many additional Ethernet type values that are assigned to various protocols; we don't show them in Figure 4.14. RFC 1700 [Reynolds and Postel 1994] contains a list of the more common types.

Queue the packet

308–315 Finally, ether_input places the packet on the selected queue or discards the packet if the queue is full. We'll see in Figures 7.23 and 21.16 that the default limit for the IP and ARP input queues is 50 (ipqmaxlen) packets each.

When ether_input returns, the device driver tells the hardware that it is ready to receive the next packet, which may already be present in the device. The packet input queues are processed when the software interrupt scheduled by schednetisr occurs (Section 1.12). Specifically, ipintr is called to process the packets on the IP input queue, and arpintr is called to process the packets on the ARP input queue.

ether_output Function

We now examine the output of Ethernet frames, which starts when a network-level protocol such as IP calls the if_output function, specified in the interface's ifnet structure. The if_output function for all Ethernet devices is ether_output (Figure 4.2). ether_output takes the data portion of an Ethernet frame, encapsulates it with the 14-byte Ethernet header, and places it on the interface's send queue. This is a large function so we describe it in four parts:

- verification,
- protocol-specific processing,
- frame construction, and
- interface queueing.

Figure 4.15 includes the first part of the function.

49–64 The arguments to ether_output are ifp, which points to the outgoing interface's ifnet structure; m0, the packet to send; dst, the destination address of the packet; and rt0, routing information.

65–67 The macro senderr is called throughout ether_output.

```
#define senderr(e) { error = (e); goto bad;}
```

senderr saves the error code and jumps to bad at the end of the function, where the packet is discarded and ether_output returns error.

If the interface is up and running, ether_output updates the last change time for the interface. Otherwise, it returns ENETDOWN.

Host route

68–74 rt0 points to the routing entry located by ip_output and passed to ether_output. If ether_output is called from BPF, rt0 can be null, in which case control passes to the code in Figure 4.16. Otherwise, the route is verified. If the route is not valid, the routing tables are consulted and EHOSTUNREACH is returned if a route cannot be located. At this point, rt0 and rt point to a valid route for the next-hop destination.

if_ethersubr.c

```
49 int
50 ether_output(ifp, m0, dst, rt0)
51 struct ifnet *ifp;
52 struct mbuf *m0;
53 struct sockaddr *dst;
54 struct rtentry *rt0;
55 {
56     short   type;
57     int     s, error = 0;
58     u_char  edst[6];
59     struct mbuf *m = m0;
60     struct rtentry *rt;
61     struct mbuf *mcopy = (struct mbuf *) 0;
62     struct ether_header *eh;
63     int     off, len = m->m_pkthdr.len;
64     struct arpcom *ac = (struct arpcom *) ifp;

65     if ((ifp->if_flags & (IFF_UP | IFF_RUNNING)) != (IFF_UP | IFF_RUNNING))
66         senderr(ENETDOWN);
67     ifp->if_lastchange = time;
68     if (rt = rt0) {
69         if ((rt->rt_flags & RTF_UP) == 0) {
70             if (rt0 = rt = rtalloc1(dst, 1))
71                 rt->rt_refcnt--;
72             else
73                 senderr(EHOSTUNREACH);
74         }
75         if (rt->rt_flags & RTF_GATEWAY) {
76             if (rt->rt_gwroute == 0)
77                 goto lookup;
78             if (((rt = rt->rt_gwroute)->rt_flags & RTF_UP) == 0) {
79                 rtfree(rt);
80                 rt = rt0;
81     lookup:     rt->rt_gwroute = rtalloc1(rt->rt_gateway, 1);

82                 if ((rt = rt->rt_gwroute) == 0)
83                     senderr(EHOSTUNREACH);
84             }
85         }
86         if (rt->rt_flags & RTF_REJECT)
87             if (rt->rt_rmx.rmx_expire == 0 ||
88                 time.tv_sec < rt->rt_rmx.rmx_expire)
89                 senderr(rt == rt0 ? EHOSTDOWN : EHOSTUNREACH);
90     }
```

if_ethersubr.c

Figure 4.15 `ether_output` function: verification.

Gateway route

75–85 If the next hop for the packet is a gateway (versus a final destination), a route to the gateway is located and pointed to by `rt`. If a gateway route cannot be found, `EHOSTUNREACH` is returned. At this point, `rt` points to the route for the next-hop destination. The next hop may be a gateway or the final destination.

Avoid ARP flooding

86–90 The RTF_REJECT flag is enabled by the ARP code to discard packets to the destination when the destination is not responding to ARP requests. This is described with Figure 21.24.

ether_output processing continues according to the destination address of the packet. Since Ethernet devices respond only to Ethernet addresses, to send a packet, ether_output must find the Ethernet address that corresponds to the IP address of the next-hop destination. The ARP protocol (Chapter 21) implements this translation. Figure 4.16 shows how the driver accesses the ARP protocol.

if_ethersubr.c
```
 91     switch (dst->sa_family) {

 92     case AF_INET:
 93         if (!arpresolve(ac, rt, m, dst, edst))
 94             return (0);         /* if not yet resolved */
 95         /* If broadcasting on a simplex interface, loopback a copy */
 96         if ((m->m_flags & M_BCAST) && (ifp->if_flags & IFF_SIMPLEX))
 97             mcopy = m_copy(m, 0, (int) M_COPYALL);
 98         off = m->m_pkthdr.len - m->m_len;
 99         type = ETHERTYPE_IP;
100         break;
101     case AF_ISO:

                                        /* OSI code */

142     case AF_UNSPEC:
143         eh = (struct ether_header *) dst->sa_data;
144         bcopy((caddr_t) eh->ether_dhost, (caddr_t) edst, sizeof(edst));
145         type = eh->ether_type;
146         break;

147     default:
148         printf("%s%d: can't handle af%d\n", ifp->if_name, ifp->if_unit,
149                dst->sa_family);
150         senderr(EAFNOSUPPORT);
151     }
```
if_ethersubr.c

Figure 4.16 ether_output function: network protocol processing.

IP output

91–101 ether_output jumps according to sa_family in the destination address. We show only the AF_INET, AF_ISO, and AF_UNSPEC cases in Figure 4.16 and have omitted the code for AF_ISO.

The AF_INET case calls arpresolve to determine the Ethernet address corresponding to the destination IP address. If the Ethernet address is already in the ARP cache, arpresolve returns 1 and ether_output proceeds. Otherwise this IP packet is held by ARP, and when ARP determines the address, it calls ether_output from the function in_arpinput.

Assuming the ARP cache contains the hardware address, `ether_output` checks if the packet is going to be broadcast and if the interface is simplex (i.e., it can't receive its own transmissions). If both tests are true, `m_copy` makes a copy of the packet. After the `switch`, the copy is queued as if it had arrived on the Ethernet interface. This is required by the definition of broadcasting; the sending host must receive a copy of the packet.

We'll see in Chapter 12 that multicast packets may also be looped back to be received on the output interface.

Explicit Ethernet output

142–146 Some protocols, such as ARP, need to specify the Ethernet destination and type explicitly. The address family constant `AF_UNSPEC` indicates that `dst` points to an Ethernet header. `bcopy` duplicates the destination address in `edst` and assigns the Ethernet type to `type`. It isn't necessary to call `arpresolve` (as for `AF_INET`) because the Ethernet destination address has been provided explicitly by the caller.

Unrecognized address families

147–151 Unrecognized address families generate a console message and `ether_output` returns `EAFNOSUPPORT`.

In the next section of `ether_output`, shown in Figure 4.17, the Ethernet frame is constructed.

if_ethersubr.c

```
152     if (mcopy)
153         (void) looutput(ifp, mcopy, dst, rt);
154     /*
155      * Add local net header.  If no space in first mbuf,
156      * allocate another.
157      */
158     M_PREPEND(m, sizeof(struct ether_header), M_DONTWAIT);
159     if (m == 0)
160         senderr(ENOBUFS);
161     eh = mtod(m, struct ether_header *);
162     type = htons((u_short) type);
163     bcopy((caddr_t) &type, (caddr_t) &eh->ether_type,
164         sizeof(eh->ether_type));
165     bcopy((caddr_t)edst, (caddr_t)eh->ether_dhost, sizeof (edst));
166     bcopy((caddr_t)ac->ac_enaddr, (caddr_t)eh->ether_shost,
167         sizeof(eh->ether_shost));
```

if_ethersubr.c

Figure 4.17 `ether_output` function: Ethernet frame construction.

Ethernet header

152–167 If the code in the `switch` made a copy of the packet, the copy is processed as if it had been received on the output interface by calling `looutput`. The loopback interface and `looutput` are described in Section 5.4.

M_PREPEND ensures that there is room for 14 bytes at the front of the packet.

> Most protocols arrange to leave room at the front of the mbuf chain so that M_PREPEND needs only to adjust some pointers (e.g., sosend for UDP output in Section 16.7 and igmp_sendreport in Section 13.6).

ether_output forms the Ethernet header from type, edst, and ac_enaddr (Figure 3.26). ac_enaddr is the unicast Ethernet address associated with the output interface and is the source Ethernet address for all frames transmitted on the interface. ether_output overwrites the source address the caller may have specified in the ether_header structure with ac_enaddr. This makes it more difficult to forge the source address of an Ethernet frame.

At this point, the mbuf contains a complete Ethernet frame except for the 32-bit CRC, which is computed by the Ethernet hardware during transmission. The code shown in Figure 4.18 queues the frame for transmission by the device.

if_ethersubr.c

```
168     s = splimp();
169     /*
170      * Queue message on interface, and start output if interface
171      * not yet active.
172      */
173     if (IF_QFULL(&ifp->if_snd)) {
174         IF_DROP(&ifp->if_snd);
175         splx(s);
176         senderr(ENOBUFS);
177     }
178     IF_ENQUEUE(&ifp->if_snd, m);
179     if ((ifp->if_flags & IFF_OACTIVE) == 0)
180         (*ifp->if_start) (ifp);
181     splx(s);
182     ifp->if_obytes += len + sizeof(struct ether_header);
183     if (m->m_flags & M_MCAST)
184         ifp->if_omcasts++;
185     return (error);

186   bad:
187     if (m)
188         m_freem(m);
189     return (error);
190 }
```

if_ethersubr.c

Figure 4.18 ether_output function: output queueing.

168–185 If the output queue is full, ether_output discards the frame and returns ENOBUFS. If the output queue is not full, the frame is placed on the interface's send queue, and the interface's if_start function transmits the next frame if the interface is not already active.

186–190 The senderr macro jumps to bad where the frame is discarded and an error code is returned.

lestart Function

The lestart function dequeues frames from the interface output queue and arranges for them to be transmitted by the LANCE Ethernet card. If the device is idle, the function is called to begin transmitting frames. An example appears at the end of ether_output (Figure 4.18), where lestart is called indirectly through the interface's if_start function.

If the device is busy, it generates an interrupt when it completes transmission of the current frame. The driver calls lestart to dequeue and transmit the next frame. Once started, the protocol layer can queue frames without calling lestart since the driver dequeues and transmits frames until the queue is empty.

Figure 4.19 shows the lestart function. lestart assumes splimp has been called to block any device interrupts.

Interface must be initialized

325–333 If the interface is not initialized, lestart returns immediately.

Dequeue frame from output queue

335–342 If the interface is initialized, the next frame is removed from the queue. If the interface output queue is empty, lestart returns.

Transmit frame and pass to BPF

343–350 leput copies the frame in m to the hardware buffer pointed to by the first argument to leput. If the interface is tapped by BPF, the frame is passed to bpf_tap. We have omitted the device-specific code that initiates the transmission of the frame from the hardware buffer.

Repeat if device is ready for more frames

359 lestart stops passing frames to the device when le->sc_txcnt equals LETBUF. Some Ethernet interfaces can queue more than one outgoing Ethernet frame. For the LANCE driver, LETBUF is the number of hardware transmit buffers available to the driver, and le->sc_txcnt keeps track of how many of the buffers are in use.

Mark device as busy

360–362 Finally, lestart turns on IFF_OACTIVE in the ifnet structure to indicate the device is busy transmitting frames.

There is an unfortunate side effect to queueing multiple frames in the device for transmission. According to [Jacobson 1988a], the LANCE chip is able to transmit queued frames with very little delay between frames. Unfortunately, some [broken] Ethernet devices drop the frames because they can't process the incoming data fast enough.

This interacts badly with an application such as NFS that sends large UDP datagrams (often greater than 8192 bytes) that are fragmented by IP and queued in the LANCE device as multiple Ethernet frames. Fragments are lost on the receiving side, resulting in many incomplete datagrams and high delays as NFS retransmits the entire UDP datagram.

Jacobson noted that Sun's LANCE driver only queued one frame at a time, perhaps to avoid this problem.

if_le.c

```
lestart(ifp)
struct ifnet *ifp;
{
    struct le_softc *le = &le_softc[ifp->if_unit];
    struct letmd *tmd;
    struct mbuf *m;
    int     len;

    if ((le->sc_if.if_flags & IFF_RUNNING) == 0)
        return (0);

                                /* device-specific code */

    do {

                                /* device-specific code */

        IF_DEQUEUE(&le->sc_if.if_snd, m);
        if (m == 0)
            return (0);
        len = leput(le->sc_r2->ler2_tbuf[le->sc_tmd], m);
        /*
         * If bpf is listening on this interface, let it
         * see the packet before we commit it to the wire.
         */
        if (ifp->if_bpf)
            bpf_tap(ifp->if_bpf, le->sc_r2->ler2_tbuf[le->sc_tmd],
                    len);

                                /* device-specific code */

    } while (++le->sc_txcnt < LETBUF);
    le->sc_if.if_flags |= IFF_OACTIVE;
    return (0);
}
```

if_le.c

Figure 4.19 `lestart` function.

4.4 `ioctl` System Call

The `ioctl` system call supports a generic command interface used by a process to access features of a device that aren't supported by the standard system calls. The prototype for `ioctl` is:

```
int ioctl(int fd, unsigned long com, ...);
```

fd is a descriptor, usually a device or network connection. Each type of descriptor supports its own set of `ioctl` commands specified by the second argument, *com*. A third argument is shown as "..." in the prototype, since it is a pointer of some type that depends on the `ioctl` command being invoked. If the command is retrieving information, the third argument must point to a buffer large enough to hold the data. In this text, we discuss only the `ioctl` commands applicable to socket descriptors.

The prototype we show for system calls is the one used by a process to issue the system call. We'll see in Chapter 15 that the function within the kernel that implements a system call has a different prototype.

We describe the implementation of the `ioctl` system call in Chapter 17 but we discuss the implementation of individual `ioctl` commands throughout the text.

The first `ioctl` commands we discuss provide access to the network interface structures that we have described. Throughout the text we summarize `ioctl` commands as shown in Figure 4.20.

Command	Third argument	Function	Description
SIOCGIFCONF	`struct ifconf *`	`ifconf`	retrieve list of interface configuration
SIOCGIFFLAGS	`struct ifreq *`	`ifioctl`	get interface flags
SIOCGIFMETRIC	`struct ifreq *`	`ifioctl`	get interface metric
SIOCSIFFLAGS	`struct ifreq *`	`ifioctl`	set interface flags
SIOCSIFMETRIC	`struct ifreq *`	`ifioctl`	set interface metric

Figure 4.20 Interface `ioctl` commands.

The first column shows the symbolic constant that identifies the `ioctl` command (the second argument, *com*). The second column shows the type of the third argument passed to the `ioctl` system call for the command shown in the first column. The third column names the function that implements the command.

Figure 4.21 shows the organization of the various functions that process `ioctl` commands. The shaded functions are the ones we describe in this chapter. The remaining functions are described in other chapters.

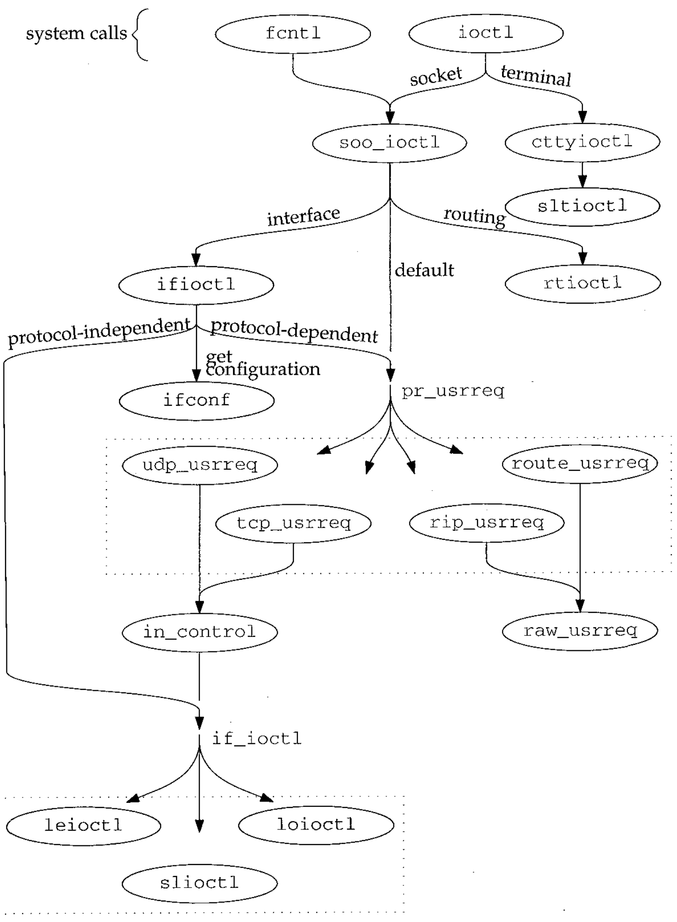


Figure 4.21 ioctl functions described in this chapter.

ifioctl Function

The ioctl system call routes the five commands shown in Figure 4.20 to the ifioctl function shown in Figure 4.22.

if.c

```
394 int
395 ifioctl(so, cmd, data, p)
396 struct socket *so;
397 int     cmd;
398 caddr_t data;
399 struct proc *p;
400 {
401     struct ifnet *ifp;
402     struct ifreq *ifr;
403     int     error;

404     if (cmd == SIOCGIFCONF)
405         return (ifconf(cmd, data));

406     ifr = (struct ifreq *) data;
407     ifp = ifunit(ifr->ifr_name);
408     if (ifp == 0)
409         return (ENXIO);
410     switch (cmd) {

            /* other interface ioctl commands (Figures 4.29 and 12.11) */

447     default:
448         if (so->so_proto == 0)
449             return (EOPNOTSUPP);
450         return ((*so->so_proto->pr_usrreq) (so, PRU_CONTROL,
451                                              cmd, data, ifp));
452     }
453     return (0);
454 }
```

if.c

Figure 4.22 ifioctl function: overview and SIOCGIFCONF.

394–405 For the SIOCGIFCONF command, ifioctl calls ifconf to construct a table of variable-length ifreq structures.

406–410 For the remaining ioctl commands, the data argument is a pointer to an ifreq structure. ifunit searches the ifnet list for an interface with the text name provided by the process in ifr->ifr_name (e.g., "sl0", "le1", or "lo0"). If there is no matching interface, ifioctl returns ENXIO. The remaining code depends on cmd and is described with Figure 4.29.

447–454 If the interface ioctl command is not recognized, ifioctl forwards the command to the user-request function of the protocol associated with the socket on which the request was made. For IP, these commands are issued on a UDP socket and udp_usrreq is called. The commands that fall into this category are described in Figure 6.10. Section 23.10 describes the udp_usrreq function in detail.

If control falls out of the switch, 0 is returned.

ifconf Function

ifconf provides a standard way for a process to discover the interfaces present and the addresses configured on a system. Interface information is represented by ifreq and ifconf structures shown in Figures 4.23 and 4.24.

```
                                                                         if.h
262 struct  ifreq {
263 #define IFNAMSIZ    16
264     char    ifr_name[IFNAMSIZ];            /* if name, e.g. "en0" */
265     union {
266         struct  sockaddr ifru_addr;
267         struct  sockaddr ifru_dstaddr;
268         struct  sockaddr ifru_broadaddr;
269         short   ifru_flags;
270         int ifru_metric;
271         caddr_t ifru_data;
272     } ifr_ifru;
273 #define ifr_addr    ifr_ifru.ifru_addr         /* address */
274 #define ifr_dstaddr ifr_ifru.ifru_dstaddr      /* other end of p-to-p link */
275 #define ifr_broadaddr   ifr_ifru.ifru_broadaddr /* broadcast address */
276 #define ifr_flags   ifr_ifru.ifru_flags        /* flags */
277 #define ifr_metric  ifr_ifru.ifru_metric       /* metric */
278 #define ifr_data    ifr_ifru.ifru_data         /* for use by interface */
279 };
                                                                         if.h
```

Figure 4.23 ifreq structure.

262–279 An ifreq structure contains the name of an interface in ifr_name. The remaining members in the union are accessed by the various ioctl commands. As usual, macros simplify the syntax required to access the members of the union.

```
                                                                         if.h
292 struct  ifconf {
293     int ifc_len;                /* size of associated buffer */
294     union {
295         caddr_t ifcu_buf;
296         struct  ifreq *ifcu_req;
297     } ifc_ifcu;
298 #define ifc_buf ifc_ifcu.ifcu_buf   /* buffer address */
299 #define ifc_req ifc_ifcu.ifcu_req   /* array of structures returned */
300 };
                                                                         if.h
```

Figure 4.24 ifconf structure.

292–300 In the ifconf structure, ifc_len is the size in bytes of the buffer pointed to by ifc_buf. The buffer is allocated by a process but filled in by ifconf with an array of variable-length ifreq structures. For the ifconf function, ifr_addr is the relevant member of the union in the ifreq structure. Each ifreq structure has a variable length because the length of ifr_addr (a sockaddr structure) varies according to the type of address. The sa_len member from the sockaddr structure must be used to locate the end of each entry. Figure 4.25 illustrates the data structures manipulated by `ifconf`.

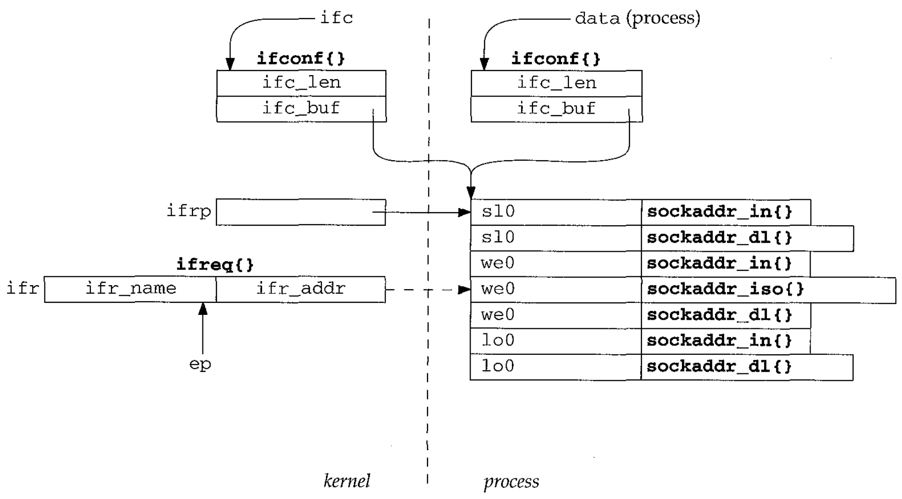


Figure 4.25 `ifconf` data structures.

In Figure 4.25, the data on the left is in the kernel and the data on the right is in a process. We'll refer to this figure as we discuss the `ifconf` function listed in Figure 4.26.

462–474 The two arguments to `ifconf` are: `cmd`, which is ignored; and `data`, which points to a copy of the `ifconf` structure specified by the process.

`ifc` is `data` cast to a `ifconf` structure pointer. `ifp` traverses the interface list starting at `ifnet` (the head of the list), and `ifa` traverses the address list for each interface. `cp` and `ep` control the construction of the text interface name within `ifr`, which is the `ifreq` structure that holds an interface name and address before they are copied to the process's buffer. `ifrp` points to this buffer and is advanced after each address is copied. `space` is the number of bytes remaining in the process's buffer, `cp` is used to search for the end of the name, and `ep` marks the last possible location for the numeric portion of the interface name.

if.c
```
462 int
463 ifconf(cmd, data)
464 int     cmd;
465 caddr_t data;
466 {
467     struct ifconf *ifc = (struct ifconf *) data;
468     struct ifnet *ifp = ifnet;
469     struct ifaddr *ifa;
470     char   *cp, *ep;
471     struct ifreq ifr, *ifrp;
472     int     space = ifc->ifc_len, error = 0;
473     ifrp = ifc->ifc_req;
474     ep = ifr.ifr_name + sizeof(ifr.ifr_name) - 2;

475     for (; space > sizeof(ifr) && ifp; ifp = ifp->if_next) {
476         strncpy(ifr.ifr_name, ifp->if_name, sizeof(ifr.ifr_name) - 2);
477         for (cp = ifr.ifr_name; cp < ep && *cp; cp++)
478             continue;
479         *cp++ = '0' + ifp->if_unit;
480         *cp = '\0';
481         if ((ifa = ifp->if_addrlist) == 0) {
482             bzero((caddr_t) & ifr.ifr_addr, sizeof(ifr.ifr_addr));
483             error = copyout((caddr_t) & ifr, (caddr_t) ifrp,
484                             sizeof(ifr));
485             if (error)
486                 break;
487             space -= sizeof(ifr), ifrp++;
488         } else
489             for (; space > sizeof(ifr) && ifa; ifa = ifa->ifa_next) {
490                 struct sockaddr *sa = ifa->ifa_addr;
491                 if (sa->sa_len <= sizeof(*sa)) {
492                     ifr.ifr_addr = *sa;
493                     error = copyout((caddr_t) & ifr, (caddr_t) ifrp,
494                                     sizeof(ifr));
495                     ifrp++;
496                 } else {
497                     space -= sa->sa_len - sizeof(*sa);
498                     if (space < sizeof(ifr))
499                         break;
500                     error = copyout((caddr_t) & ifr, (caddr_t) ifrp,
501                                     sizeof(ifr.ifr_name));
502                     if (error == 0)
503                         error = copyout((caddr_t) sa,
504                                   (caddr_t) & ifrp->ifr_addr, sa->sa_len);
505                     ifrp = (struct ifreq *)
506                         (sa->sa_len + (caddr_t) & ifrp->ifr_addr);
507                 }
508                 if (error)
509                     break;
510                 space -= sizeof(ifr);
511             }
512     }
513     ifc->ifc_len -= space;
514     return (error);
515 }
```
if.c

Figure 4.26 ifconf function.

475–488 The for loop traverses the list of interfaces. For each interface, the text name is copied to ifr_name followed by the text representation of the if_unit number. If no addresses have been assigned to the interface, an address of all 0s is constructed, the resulting ifreq structure is copied to the process, space is decreased, and ifrp is advanced.

489–515 If the interface has one or more addresses, the for loop processes each one. The address is added to the interface name in ifr and then ifr is copied to the process. Addresses longer than a standard sockaddr structure don't fit in ifr and are copied directly out to the process. After each address, space and ifrp are adjusted. After all the interfaces are processed, the length of the buffer is updated (ifc->ifc_len) and ifconf returns. The ioctl system call takes care of copying the new contents of the ifconf structure back to the ifconf structure in the process.

Example

Figure 4.27 shows the configuration of the interface structures after the Ethernet, SLIP, and loopback interfaces have been initialized.

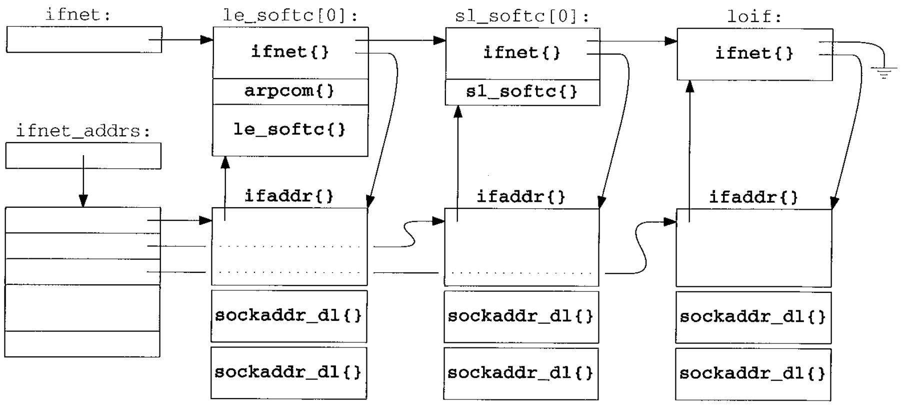


Figure 4.27 Interface and address data structures.

Figure 4.28 shows the contents of ifc and buffer after the following code is executed.

```
struct ifconf ifc;     /* SIOCGIFCONF adjusts this */
char buffer[144];      /* contains interface addresses when ioctl returns */
int s;                 /* any socket */

ifc.ifc_len = 144;
ifc.ifc_buf = buffer;
if (ioctl(s, SIOCGIFCONF, &ifc) < 0 ) {
    perror("ioctl failed");
    exit(1);
}
```

There are no restrictions on the type of socket specified with the SIOCGIFCONF command, which, as we have seen, returns the addresses for all protocol families.

In Figure 4.28, ifc_len has been changed from 144 to 108 by ioctl since the three addresses returned in the buffer only occupy 108 (3×36) bytes. Three sockaddr_dl addresses are returned and the last 36 bytes of the buffer are unused. The first 16 bytes of each entry contain the text name of the interface. In this case only 3 of the 16 bytes are used.

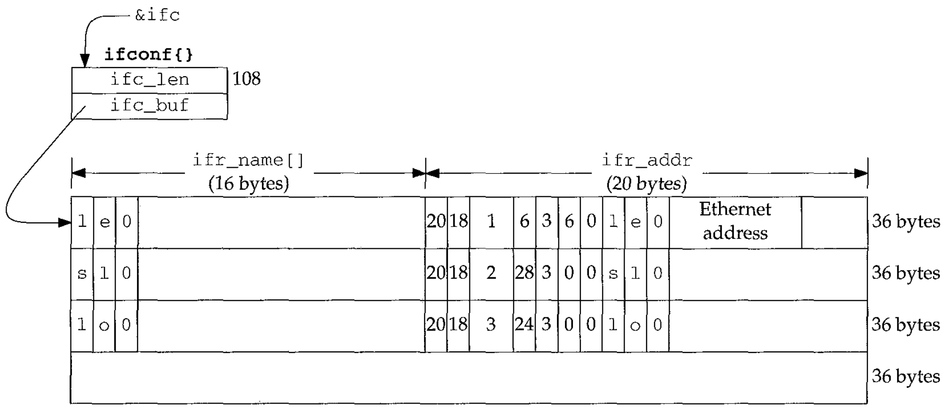


Figure 4.28 Data returned by the SIOCGIFCONF command.

ifr_addr has the form of a sockaddr structure, so the first value is the length (20 bytes) and the second value is the type of address (18, AF_LINK). The next value is sdl_index, which is different for each interface as is sdl_type (6, 28, and 24 correspond to IFT_ETHER, IFT_SLIP, and IFT_LOOP).

The next three values are sa_nlen (the length of the text name), sa_alen (the length of the hardware address), and sa_slen (unused). sa_nlen is 3 for all three entries. sa_alen is 6 for the Ethernet address and 0 for both the SLIP and loopback interfaces. sa_slen is always 0.

Finally, the text interface name appears, followed by the hardware address (Ethernet only). Neither the SLIP nor the loopback interface store a hardware-level address in the sockaddr_dl structure.

In the example, only sockaddr_dl addresses are returned (because no other address types were configured in Figure 4.27), so each entry in the buffer is the same size. If other addresses (e.g., IP or OSI addresses) were configured for an interface, they would be returned along with the sockaddr_dl addresses, and the size of each entry would vary according to the type of address returned.

Generic Interface ioctl commands

The four remaining interface commands from Figure 4.20 (SIOCGIFFLAGS, SIOCGIFMETRIC, SIOCSIFFLAGS, and SIOCSIFMETRIC) are handled by the ifioctl function. Figure 4.29 shows the case statements for these commands.

SIOCGIFFLAGS and SIOCGIFMETRIC

410–416 For the two SIOCG*xxx* commands, ifioctl copies the if_flags or if_metric value for the interface into the ifreq structure. For the flags, the ifr_flags member of the union is used and for the metric, the ifr_metric member is used (Figure 4.23).

if.c
```
410     switch (cmd) {
411     case SIOCGIFFLAGS:
412         ifr->ifr_flags = ifp->if_flags;
413         break;

414     case SIOCGIFMETRIC:
415         ifr->ifr_metric = ifp->if_metric;
416         break;

417     case SIOCSIFFLAGS:
418         if (error = suser(p->p_ucred, &p->p_acflag))
419             return (error);
420         if (ifp->if_flags & IFF_UP && (ifr->ifr_flags & IFF_UP) == 0) {
421             int     s = splimp();
422             if_down(ifp);
423             splx(s);
424         }
425         if (ifr->ifr_flags & IFF_UP && (ifp->if_flags & IFF_UP) == 0) {
426             int     s = splimp();
427             if_up(ifp);
428             splx(s);
429         }
430         ifp->if_flags = (ifp->if_flags & IFF_CANTCHANGE) |
431             (ifr->ifr_flags & ~IFF_CANTCHANGE);
432         if (ifp->if_ioctl)
433             (void) (*ifp->if_ioctl) (ifp, cmd, data);
434         break;

435     case SIOCSIFMETRIC:
436         if (error = suser(p->p_ucred, &p->p_acflag))
437             return (error);
438         ifp->if_metric = ifr->ifr_metric;
439         break;
```
if.c

Figure 4.29 `ifioctl` function: flags and metrics.

`SIOCSIFFLAGS`

417–429 To change the interface flags, the calling process must have superuser privileges. If the process is shutting down a running interface or bringing up an interface that isn't running, `if_down` or `if_up` are called respectively.

Ignore `IFF_CANTCHANGE` flags

430–434 Recall from Figure 3.7 that some interface flags cannot be changed by a process. The expression `(ifp->if_flags & IFF_CANTCHANGE)` clears the interface flags that *can* be changed by the process, and the expression `(ifr->ifr_flags & ~IFF_CANTCHANGE)` clears the flags in the *request* that may *not* be changed by the process. The two expressions are ORed together and saved as the new value for `ifp->if_flags`. Before returning, the request is passed to the `if_ioctl` function associated with the device (e.g., `leioctl` for the LANCE driver—Figure 4.31).

SIOCSIFMETRIC

435–439 Changing the interface metric is easier; as long as the process has superuser privileges, `ifioctl` copies the new metric into `if_metric` for the interface.

`if_down` and `if_up` Functions

With the `ifconfig` program, an administrator can enable and disable an interface by setting or clearing the `IFF_UP` flag through the `SIOCSIFFLAGS` command. Figure 4.30 shows the code for the `if_down` and `if_up` functions.

if.c

```
292 void
293 if_down(ifp)
294 struct ifnet *ifp;
295 {
296     struct ifaddr *ifa;

297     ifp->if_flags &= ~IFF_UP;
298     for (ifa = ifp->if_addrlist; ifa; ifa = ifa->ifa_next)
299         pfctlinput(PRC_IFDOWN, ifa->ifa_addr);
300     if_qflush(&ifp->if_snd);
301     rt_ifmsg(ifp);
302 }

308 void
309 if_up(ifp)
310 struct ifnet *ifp;
311 {
312     struct ifaddr *ifa;

313     ifp->if_flags |= IFF_UP;
314     rt_ifmsg(ifp);
315 }
```

if.c

Figure 4.30 `if_down` and `if_up` functions.

292–302 When an interface is shut down, the `IFF_UP` flag is cleared and the `PRC_IFDOWN` command is issued by `pfctlinput` (Section 7.7) for each address associated with the interface. This gives each protocol an opportunity to respond to the interface being shut down. Some protocols, such as OSI, terminate connections using the interface. IP attempts to reroute connections through other interfaces if possible. TCP and UDP ignore failing interfaces and rely on the routing protocols to find alternate paths for the packets.

`if_qflush` discards any packets queued for the interface. The routing system is notified of the change by `rt_ifmsg`. TCP retransmits the lost packets automatically; UDP applications must explicitly detect and respond to this condition on their own.

308–315 When an interface is enabled, the `IFF_UP` flag is set and `rt_ifmsg` notifies the routing system that the interface status has changed.

Ethernet, SLIP, and Loopback

We saw in Figure 4.29 that for the `SIOCSIFFLAGS` command, `ifioctl` calls the `if_ioctl` function for the interface. In our three sample interfaces, the `slioctl` and `loioctl` functions return `EINVAL` for this command, which is ignored by `ifioctl`. Figure 4.31 shows the `leioctl` function and `SIOCSIFFLAGS` processing of the LANCE Ethernet driver.

if_le.c

```
leioctl(ifp, cmd, data)
struct ifnet *ifp;
int     cmd;
caddr_t data;
{
    struct ifaddr *ifa = (struct ifaddr *) data;
    struct le_softc *le = &le_softc[ifp->if_unit];
    struct lereg1 *ler1 = le->sc_r1;
    int     s = splimp(), error = 0;

    switch (cmd) {

                    /* SIOCSIFADDR code (Figure 6.28) */

    case SIOCSIFFLAGS:
        if ((ifp->if_flags & IFF_UP) == 0 &&
            ifp->if_flags & IFF_RUNNING) {
            LERDWR(le->sc_r0, LE_STOP, ler1->ler1_rdp);
            ifp->if_flags &= ~IFF_RUNNING;
        } else if (ifp->if_flags & IFF_UP &&
                   (ifp->if_flags & IFF_RUNNING) == 0)
            leinit(ifp->if_unit);
        /*
         * If the state of the promiscuous bit changes, the interface
         * must be reset to effect the change.
         */
        if (((ifp->if_flags ^ le->sc_iflags) & IFF_PROMISC) &&
            (ifp->if_flags & IFF_RUNNING)) {
            le->sc_iflags = ifp->if_flags;
            lereset(ifp->if_unit);
            lestart(ifp);
        }
        break;

           /* SIOCADDMULTI and SIOCDELMULTI code (Figure 12.31) */

    default:
        error = EINVAL;
    }
    splx(s);
    return (error);
}
```

if_le.c

Figure 4.31 `leioctl` function: `SIOCSIFFLAGS`.

614–623 leioctl casts the third argument, data, to an ifaddr structure pointer and saves the value in ifa. The le pointer references the le_softc structure indexed by ifp->if_unit. The switch statement, based on cmd, makes up the main body of the function.

638–656 Only the SIOCSIFFLAGS case is shown in Figure 4.31. By the time ifioctl calls leioctl, the interface flags have been changed. The code shown here forces the physical interface into a state that matches the configuration of the flags. If the interface is going down (IFF_UP is not set), but the interface is operating, the interface is shut down. If the interface is going up but is not operating, the interface is initialized and restarted.

If the promiscuous bit has been changed, the interface is shut down, reset, and restarted to implement the change.

The expression including the exclusive OR and IFF_PROMISC is true only if the request changes the IFF_PROMISC bit.

672–677 The default case for unrecognized commands posts EINVAL, which is returned at the end of the function.

4.5 Summary

In this chapter we described the implementation of the LANCE Ethernet device driver, which we refer to throughout the text. We saw how the Ethernet driver detects broadcast and multicast addresses on input, how the Ethernet and 802.3 encapsulations are detected, and how incoming frames are demultiplexed to the appropriate protocol queue. In Chapter 21 we'll see how IP addresses (unicast, broadcast, and multicast) are converted into the correct Ethernet addresses on output.

Finally, we discussed the protocol-specific ioctl commands that access the interface-layer data structures.

Exercises

4.1 In leread, the M_MCAST flag (in addition to M_BCAST) is always set when a broadcast packet is received. Compare this behavior to the code in ether_input. Why are the flags set in leread and ether_input? Does it matter? Which is correct?

4.2 In ether_input (Figure 4.13), what would happen if the test for the broadcast address and the test for a multicast address were swapped? What would happen if the if on the test for a multicast address were not preceded by an else?

5

Interfaces: SLIP and Loopback

5.1 Introduction

In Chapter 4 we looked at the Ethernet interface. In this chapter we describe the SLIP and loopback interfaces, as well as the ioctl commands used to configure all network interfaces. The TCP compression algorithm used by the SLIP driver is described in Section 29.13. The loopback driver is straightforward and we discuss it here in its entirety.

Figure 5.1, which also appeared as Figure 4.2, lists the entry points to our three example drivers.

ifnet	Ethernet	SLIP	Loopback	Description
if_init	leinit			initialize hardware
if_output	ether_output	sloutput	looutput	accept and queue packet for transmission
if_start	lestart			begin transmission of frame
if_done				output complete (unused)
if_ioctl	leioctl	slioctl	loioctl	handle ioctl commands from a process
if_reset	lereset			reset the device to a known state
if_watchdog				watch the device for failures or collect statistics

Figure 5.1 Interface functions for the example drivers.

5.2 Code Introduction

The files containing code for SLIP and loopback drivers are listed in Figure 5.2.

File	Description
net/if_slvar.h	SLIP definitions
net/if_sl.c	SLIP driver functions
net/if_loop.c	loopback driver

Figure 5.2 Files discussed in this chapter.

Global Variables

The SLIP and loopback interface structures are described in this chapter.

Variable	Datatype	Description
sl_softc	struct sl_softc []	SLIP interface
loif	struct ifnet	loopback interface

Figure 5.3 Global variables introduced in this chapter.

`sl_softc` is an array, since there can be many SLIP interfaces. `loif` is not an array, since there can be only one loopback interface.

Statistics

The statistics from the `ifnet` structure described in Chapter 4 are also updated by the SLIP and loopback drivers. One other variable (which is not in the `ifnet` structure) collects statistics; it is shown in Figure 5.4.

Variable	Description	Used by SNMP
tk_nin	#bytes received by any serial interface (updated by SLIP driver)	

Figure 5.4 `tk_nin` variable.

5.3 SLIP Interface

A SLIP interface communicates with a remote system across a standard asynchronous serial line. As with Ethernet, SLIP defines a standard way to frame IP packets as they are transmitted on the serial line. Figure 5.5 shows the encapsulation of an IP packet into a SLIP frame when the IP packet contains SLIP's reserved characters.

Packets are separated by the SLIP END character `0xc0`. If the END character appears in the IP packet, it is prefixed with the SLIP ESC character `0xdb` and transmitted as `0xdc` instead. When the ESC character appears in the IP packet, it is prefixed with the ESC character `0xdb` and transmitted as `0xdd`.

Since there is no type field in SLIP frames (as there is with Ethernet), SLIP is suitable only for carrying IP packets.

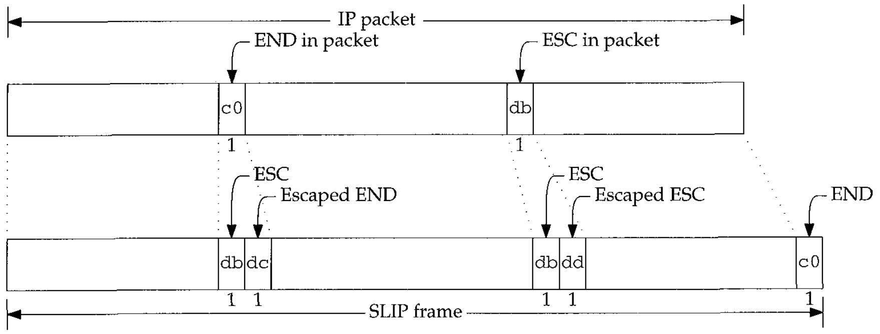


Figure 5.5 SLIP encapsulation of an IP packet.

SLIP is described in RFC 1055 [Romkey 1988], where its many weaknesses and nonstandard status are also stated. Volume 1 contains a more detailed description of SLIP encapsulation.

The Point-to-Point Protocol (PPP) was designed to address SLIP's problems and to provide a standard method for transmitting frames across a serial link. PPP is defined in RFC 1332 [McGregor 1992] and RFC 1548 [Simpson 1993]. Net/3 does not contain an implementation of PPP, so we do not discuss it in this text. See Section 2.6 of Volume 1 for more information regarding PPP. Appendix B describes where to obtain a reference implementation of PPP.

The SLIP Line Discipline: `SLIPDISC`

In Net/3 the SLIP interface relies on an asynchronous serial device driver to send and receive the data. Traditionally these device drivers have been called TTYs (teletypes). The Net/3 TTY subsystem includes the notion of a *line discipline* that acts as a filter between the physical device and I/O system calls such as `read` and `write`. A line discipline implements features such as line editing, newline and carriage-return processing, tab expansion, and more. The SLIP interface appears as a line discipline to the TTY subsystem, but it does not pass incoming data to a process reading from the device and does not accept outgoing data from a process writing to the device. Instead, the SLIP interface passes incoming packets to the IP input queue and accepts outgoing packets through the `if_output` function in SLIP's `ifnet` structure. The kernel identifies line disciplines by an integer constant, which for SLIP is `SLIPDISC`.

Figure 5.6 shows a traditional line discipline on the left and the SLIP discipline on the right. We show the process on the right as `slattach` since it is the program that initializes a SLIP interface. The details of the TTY subsystem and line disciplines are outside the scope of this text. We present only the information required to understand the workings of the SLIP code. For more information about the TTY subsystem see [Leffler et al. 1989]. Figure 5.7 lists the functions that implement the SLIP driver. The middle columns indicate whether the function implements line discipline features, network interface features, or both.

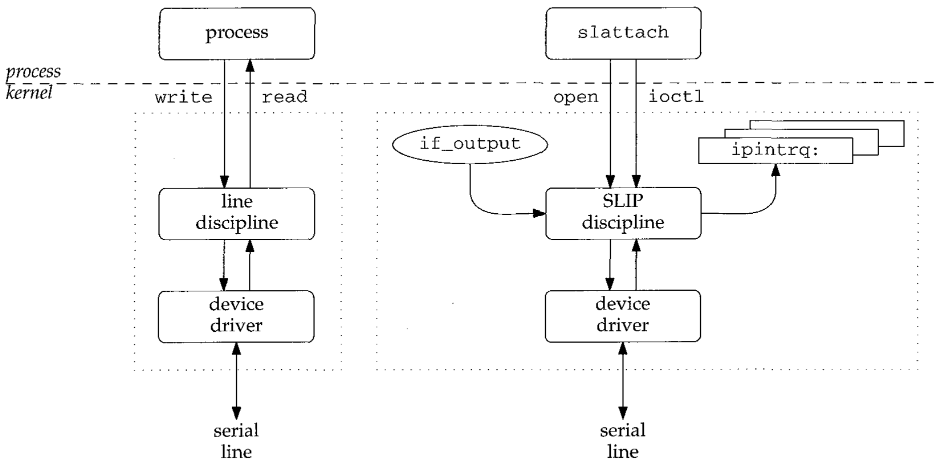


Figure 5.6 The SLIP interface as a line discipline.

Function	Network Interface	Line Discipline	Description
slattach	•		initialize and attach sl_softc structures to ifnet list
slinit	•		initialize the SLIP data structures
sloutput	•		queue outgoing packets for transmission on associated TTY device
slioctl	•		process socket ioctl requests
sl_btom	•		convert a device buffer to an mbuf chain
slopen		•	attach sl_softc structure to TTY device and initialize driver
slclose		•	detach sl_softc structures from TTY device, mark interface as down, and release memory
sltioctl		•	process TTY ioctl commands
slstart	•	•	dequeue packet and begin transmitting data on TTY device
slinput	•	•	process incoming byte from TTY device, queue incoming packet if an entire frame has been received

Figure 5.7 The functions in the SLIP device driver.

The SLIP driver in Net/3 supports compression of TCP packet headers for better throughput. We discuss header compression in Section 29.13, so Figure 5.7 omits the functions that implement this feature.

The Net/3 SLIP interface also supports an escape sequence. When detected by the receiver, the sequence shuts down SLIP processing and returns the device to the standard line discipline. We omit this processing from our discussion.

Figure 5.8 shows the complex relationship between SLIP as a line discipline and SLIP as a network interface.

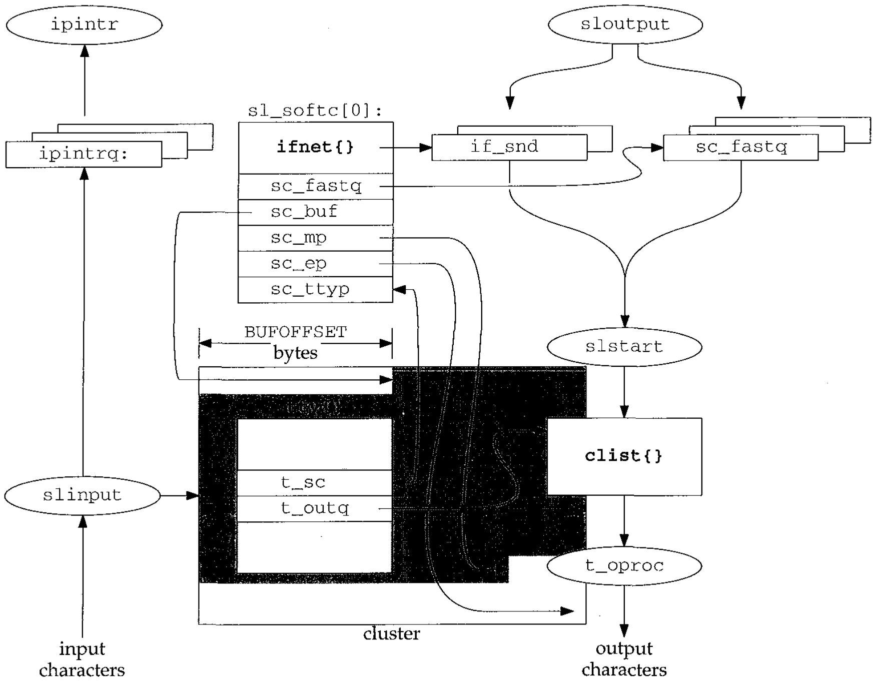


Figure 5.8 SLIP device driver.

In Net/3 sc_ttyp and t_sc point to the tty structure and the sl_softc[0] structure. Instead of cluttering the figure with two arrows, we use a double-ended arrow positioned at each pointer to illustrated the two links between the structures.

Figure 5.8 contains a lot of information:

- The network interface is represented by the sl_softc structure and the TTY device by the tty structure.
- Incoming bytes are stored in the cluster (shown behind the tty structure). When a complete SLIP frame is received, the enclosed IP packet is put on the ipintrq by slinput.
- Outgoing packets are dequeued from if_snd or sc_fastq, converted to SLIP frames, and passed to the TTY device by slstart. The TTY buffers outgoing bytes in the clist structure. The t_oproc function drains and transmits the bytes held in the clist structure.

SLIP Initialization: `slopen` and `slinit`

We discussed in Section 3.7 how `slattach` initializes the `sl_softc` structures. The interface remains initialized but inoperative until a program (usually `slattach`) opens a TTY device (e.g., `/dev/tty01`) and issues an `ioctl` command to replace the standard line discipline with the SLIP discipline. At this point the TTY subsystem calls the line discipline's open function (in this case `slopen`), which establishes the association between a particular TTY device and a particular SLIP interface. `slopen` is shown in Figure 5.9.

if_sl.c

```
181 int
182 slopen(dev, tp)
183 dev_t   dev;
184 struct tty *tp;
185 {
186     struct proc *p = curproc;    /* XXX */
187     struct sl_softc *sc;
188     int     nsl;
189     int     error;

190     if (error = suser(p->p_ucred, &p->p_acflag))
191         return (error);

192     if (tp->t_line == SLIPDISC)
193         return (0);

194     for (nsl = NSL, sc = sl_softc; --nsl >= 0; sc++)
195         if (sc->sc_ttyp == NULL) {
196             if (slinit(sc) == 0)
197                 return (ENOBUFS);
198             tp->t_sc = (caddr_t) sc;
199             sc->sc_ttyp = tp;
200             sc->sc_if.if_baudrate = tp->t_ospeed;
201             ttyflush(tp, FREAD | FWRITE);
202             return (0);
203         }
204     return (ENXIO);
205 }
```

if_sl.c

Figure 5.9 The `slopen` function.

181–193 Two arguments are passed to `slopen`: `dev`, a kernel device identifier that `slopen` does not use; and `tp`, a pointer to the `tty` structure associated with the TTY device. First some precautions: if the process does not have superuser privileges, or if the TTY's line discipline is set to `SLIPDISC` already, `slopen` returns immediately.

194–205 The `for` loop searches the array of `sl_softc` structures for the first unused entry, calls `slinit` (Figure 5.10), joins the `tty` and `sl_softc` structures by `t_sc` and `sc_ttyp`, and copies the TTY output speed (`t_ospeed`) into the SLIP interface. `ttyflush` discards any pending input or output data in the TTY queues. `slopen` returns `ENXIO` if a SLIP interface structure is not available, or 0 if it was successful.

Notice that the first available `sl_softc` structure is associated with the TTY device. There need not be a fixed mapping between TTY devices and SLIP interfaces if the system has more than one SLIP line. In fact, the mapping depends on the order in which `slattach` opens and closes the TTY devices.

The `slinit` function shown in Figure 5.10 initializes the `sl_softc` structure.

if_sl.c

```
156 static int
157 slinit(sc)
158 struct sl_softc *sc;
159 {
160     caddr_t p;

161     if (sc->sc_ep == (u_char *) 0) {
162         MCLALLOC(p, M_WAIT);
163         if (p)
164             sc->sc_ep = (u_char *) p + SLBUFSIZE;
165         else {
166             printf("sl%d: can't allocate buffer\n", sc - sl_softc);
167             sc->sc_if.if_flags &= ~IFF_UP;
168             return (0);
169         }
170     }
171     sc->sc_buf = sc->sc_ep - SLMAX;
172     sc->sc_mp = sc->sc_buf;
173     sl_compress_init(&sc->sc_comp);
174     return (1);
175 }
```

if_sl.c

Figure 5.10 The `slinit` function.

156–175 The `slinit` function allocates an mbuf cluster and attaches it to the `sl_softc` structure with three pointers. Incoming bytes are stored in the cluster until an entire SLIP frame has been received. `sc_buf` always points to the start of the packet in the cluster, `sc_mp` points to the location of the next byte to be received, and `sc_ep` points to the end of the cluster. `sl_compress_init` initializes the TCP header compression state for this link (Section 29.13).

In Figure 5.8 we see that `sc_buf` does not point to the first byte in the cluster. `slinit` leaves room for 148 bytes (`BUFOFFSET`), as the incoming packet may have a compressed header that will expand to fill this space. The bytes that have already been received are shaded in the cluster. We see that `sc_mp` points to the byte just after the last byte received and `sc_ep` points to the end of the cluster. Figure 5.11 shows the relationships between several SLIP constants.

All that remains to make the interface operational is to assign it an IP address. As with the Ethernet driver, we postpone the discussion of address assignment until Section 6.6.

Constant	Value	Description
MCLBYTES	2048	size of an mbuf cluster
SLBUFSIZE	2048	maximum size of an uncompressed SLIP packet—including a BPF header
SLIP_HDRLEN	16	size of SLIP BPF header
BUFOFFSET	148	maximum size of an expanded TCP/IP header plus room for a BPF header
SLMAX	1900	maximum size of a compressed SLIP packet stored in a cluster
SLMTU	296	optimal size of SLIP packet; results in minimal delay with good bulk throughput
SLIP_HIWAT	100	maximum number of bytes to queue in TTY output queue
BUFOFFSET + SLMAX = SLBUFSIZE = MCLBYTES		

Figure 5.11 SLIP constants.

SLIP Input Processing: `slinput`

The TTY device driver delivers incoming characters to the SLIP line discipline one at a time by calling `slinput`. Figure 5.12 shows the `slinput` function but omits the end-of-frame processing, which is discussed separately.

if_sl.c

```
void
slinput(c, tp)
int     c;
struct tty *tp;
{
    struct sl_softc *sc;
    struct mbuf *m;
    int     len;
    int     s;
    u_char  chdr[CHDR_LEN];

    tk_nin++;
    sc = (struct sl_softc *) tp->t_sc;
    if (sc == NULL)
        return;
    if (c & TTY_ERRORMASK || ((tp->t_state & TS_CARR_ON) == 0 &&
                              (tp->t_cflag & CLOCAL) == 0)) {
        sc->sc_flags |= SC_ERROR;
        return;
    }
    c &= TTY_CHARMASK;

    ++sc->sc_if.if_ibytes;

    switch (c) {

    case TRANS_FRAME_ESCAPE:
        if (sc->sc_escape)
            c = FRAME_ESCAPE;
        break;
553     case TRANS_FRAME_END:
554         if (sc->sc_escape)
555             c = FRAME_END;
556         break;

557     case FRAME_ESCAPE:
558         sc->sc_escape = 1;
559         return;

560     case FRAME_END:

                              /* FRAME_END code (Figure 5.13) */

636     }
637     if (sc->sc_mp < sc->sc_ep) {
638         *sc->sc_mp++ = c;
639         sc->sc_escape = 0;
640         return;
641     }
642     /* can't put lower; would miss an extra frame */
643     sc->sc_flags |= SC_ERROR;

644   error:
645     sc->sc_if.if_ierrors++;
646   newpack:
647     sc->sc_mp = sc->sc_buf = sc->sc_ep - SLMAX;
648     sc->sc_escape = 0;
649 }
```
if_sl.c

Figure 5.12 slinput function.

527–545 The arguments to slinput are c, the next input character; and tp, a pointer to the device's tty structure. The global integer tk_nin counts the incoming characters for all TTY devices. slinput converts tp->t_sc to sc, a pointer to an sl_softc structure. If there is no interface associated with the TTY device, slinput returns immediately.

The first argument to slinput is an integer. In addition to the received character, c contains control information sent from the TTY device driver in the high-order bits. If an error is indicated in c or the modem-control lines are not enabled and should not be ignored, SC_ERROR is set and slinput returns. Later, when slinput processes the END character, the frame is discarded. The CLOCAL flag indicates that the system should treat the line as a local line (i.e., not a dialup line) and should not expect to see modem-control signals.

546–636 slinput discards the control bits in c by masking it with TTY_CHARMASK, updates the count of bytes received on the interface, and jumps based on the received character:

- If c is an escaped ESC character and the *previous* character was an ESC, slinput replaces c with an ESC character.
- If c is an escaped END character and the *previous* character was an ESC, slinput replaces c with an END character.

- If c is the SLIP ESC character, sc_escape is set and slinput returns immediately (i.e., the ESC character is discarded).
- If c is the SLIP END character, the packet is put on the IP input queue. The processing for the SLIP frame end character is shown in Figure 5.13.

The common flow of control through this switch statement is to fall through (there is no default case). Most bytes are data and don't match any of the four cases. Control also falls through the switch in the first two cases.

637–649 If control falls through the switch, the received character is part of the IP packet. The character is stored in the cluster (if there is room), the pointers are advanced, sc_escape is cleared, and slinput returns.

If the cluster is full, the character is discarded and slinput sets SC_ERROR. Control reaches error when the cluster is full or when an error is detected in the end-of-frame processing. At newpack the cluster pointers are reset for a new packet, sc_escape is cleared, and slinput returns.

Figure 5.13 shows the FRAME_END code omitted from Figure 5.12.

if_sl.c

```
    case FRAME_END:
        if (sc->sc_flags & SC_ERROR) {
            sc->sc_flags &= ~SC_ERROR;
            goto newpack;
        }
        len = sc->sc_mp - sc->sc_buf;
        if (len < 3)
            /* less than min length packet - ignore */
            goto newpack;

        if (sc->sc_bpf) {
            /*
             * Save the compressed header, so we
             * can tack it on later.  Note that we
             * will end up copying garbage in some
             * cases but this is okay.  We remember
             * where the buffer started so we can
             * compute the new header length.
             */
            bcopy(sc->sc_buf, chdr, CHDR_LEN);
        }
        if ((c = (*sc->sc_buf & 0xf0)) != (IPVERSION << 4)) {
            if (c & 0x80)
                c = TYPE_COMPRESSED_TCP;
            else if (c == TYPE_UNCOMPRESSED_TCP)
                *sc->sc_buf &= 0x4f;    /* XXX */
            /*
             * We've got something that's not an IP packet.
             * If compression is enabled, try to decompress it.
             * Otherwise, if auto-enable compression is on and
             * it's a reasonable packet, decompress it and then
             * enable compression.  Otherwise, drop it.
             */
```

```
592             if (sc->sc_if.if_flags & SC_COMPRESS) {
593                 len = sl_uncompress_tcp(&sc->sc_buf, len,
594                                         (u_int) c, &sc->sc_comp);
595                 if (len <= 0)
596                     goto error;
597             } else if ((sc->sc_if.if_flags & SC_AUTOCOMP) &&
598                        c == TYPE_UNCOMPRESSED_TCP && len >= 40) {
599                 len = sl_uncompress_tcp(&sc->sc_buf, len,
600                                         (u_int) c, &sc->sc_comp);
601                 if (len <= 0)
602                     goto error;
603                 sc->sc_if.if_flags |= SC_COMPRESS;
604             } else
605                 goto error;
606         }
607         if (sc->sc_bpf) {
608             /*
609              * Put the SLIP pseudo-"link header" in place.
610              * We couldn't do this any earlier since
611              * decompression probably moved the buffer
612              * pointer.  Then, invoke BPF.
613              */
614             u_char *hp = sc->sc_buf - SLIP_HDRLEN;

615             hp[SLX_DIR] = SLIPDIR_IN;
616             bcopy(chdr, &hp[SLX_CHDR], CHDR_LEN);
617             bpf_tap(sc->sc_bpf, hp, len + SLIP_HDRLEN);
618         }
619         m = sl_btom(sc, len);
620         if (m == NULL)
621             goto error;

622         sc->sc_if.if_ipackets++;
623         sc->sc_if.if_lastchange = time;
624         s = splimp();
625         if (IF_QFULL(&ipintrq)) {
626             IF_DROP(&ipintrq);
627             sc->sc_if.if_ierrors++;
628             sc->sc_if.if_iqdrops++;
629             m_freem(m);
630         } else {
631             IF_ENQUEUE(&ipintrq, m);
632             schednetisr(NETISR_IP);
633         }
634         splx(s);
635         goto newpack;
```
if_sl.c

Figure 5.13 `slinput` function: end-of-frame processing.

560–579 `slinput` discards an incoming SLIP packet immediately if `SC_ERROR` was set while the packet was being received or if the packet is less than 3 bytes in length (remember that the packet may be compressed).

If the SLIP interface is tapped by BPF, `slinput` saves a copy of the (possibly compressed) header in the `chdr` array.

580–606 By examining the first byte of the packet, slinput determines if it is an uncompressed IP packet, a compressed TCP segment, or an uncompressed TCP segment. The type is saved in c and the type information is removed from the first byte of data (Section 29.13). If the packet appears to be compressed and compression is enabled, sl_uncompress_tcp attempts to uncompress the packet. If compression is not enabled, auto-enable compression is on, and if the packet is large enough sl_uncompress_tcp is also called. If it is a compressed TCP packet, the compression flag is set.

slinput discards packets it does not recognize by jumping to error. Section 29.13 discusses the header compression techniques in more detail. The cluster now contains a complete uncompressed packet.

607–618 After SLIP has decompressed the packet, the header and data are passed to BPF. Figure 5.14 shows the layout of the buffer constructed by slinput.

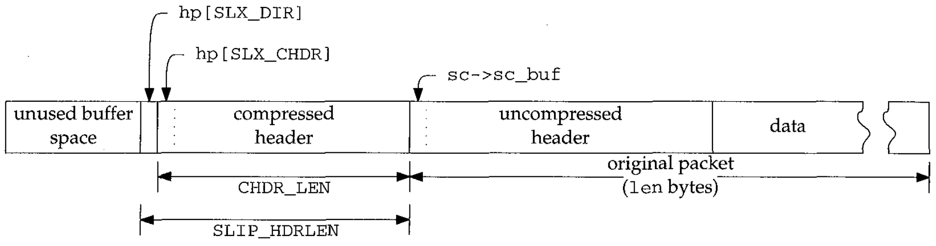


Figure 5.14 SLIP packet in BPF format.

The first byte of the BPF header encodes the direction of the packet, in this case incoming (SLIPDIR_IN). The next 15 bytes contain the compressed header. The entire packet is passed to bpf_tap.

619–635 sl_btom converts the cluster to an mbuf chain. If the packet is small enough to fit in a single mbuf, sl_btom copies the packet from the cluster to a newly allocated mbuf packet header; otherwise sl_btom attaches the cluster to an mbuf and allocates a new cluster for the interface. This is faster than copying from one cluster to another. We do not show sl_btom in this text.

Since only IP packets are transmitted on a SLIP interface, slinput does not have to select a protocol queue (as it does in the Ethernet driver). The packet is queued on ipintrq, an IP software interrupt is scheduled, and slinput jumps to newpack, where it updates the cluster packet pointers and clears sc_escape.

While the SLIP driver increments if_ierrors if the packet cannot be queued on ipintrq, neither the Ethernet nor loopback drivers increment this statistic in the same situation.

Access to the IP input queue must be protected by splimp even though slinput is called at spltty. Recall from Figure 1.14 that an splimp interrupt can preempt spltty processing.

SLIP Output Processing: `sloutput`

As with all network interfaces, output processing begins when a network-level protocol calls the interface's `if_output` function. For the Ethernet driver, the function is `ether_output`. For SLIP, the function is `sloutput` (Figure 5.15).

if_sl.c

```
int
sloutput(ifp, m, dst, rtp)
struct ifnet *ifp;
struct mbuf *m;
struct sockaddr *dst;
struct rtentry *rtp;
{
    struct sl_softc *sc = &sl_softc[ifp->if_unit];
    struct ip *ip;
    struct ifqueue *ifq;
    int     s;

    /*
     * Cannot happen (see slioctl).  Someday we will extend
     * the line protocol to support other address families.
     */
    if (dst->sa_family != AF_INET) {
        printf("sl%d: af%d not supported\n", sc->sc_if.if_unit,
               dst->sa_family);
        m_freem(m);
        sc->sc_if.if_noproto++;
        return (EAFNOSUPPORT);
    }
    if (sc->sc_ttyp == NULL) {
        m_freem(m);
        return (ENETDOWN);      /* sort of */
    }
    if ((sc->sc_ttyp->t_state & TS_CARR_ON) == 0 &&
        (sc->sc_ttyp->t_cflag & CLOCAL) == 0) {
        m_freem(m);
        return (EHOSTUNREACH);
    }
    ifq = &sc->sc_if.if_snd;
    ip = mtod(m, struct ip *);
    if (sc->sc_if.if_flags & SC_NOICMP && ip->ip_p == IPPROTO_ICMP) {
        m_freem(m);
        return (ENETRESET);     /* XXX ? */
    }
    if (ip->ip_tos & IPTOS_LOWDELAY)
        ifq = &sc->sc_fastq;
    s = splimp();
    if (IF_QFULL(ifq)) {
        IF_DROP(ifq);
        m_freem(m);
        splx(s);
        sc->sc_if.if_oerrors++;
        return (ENOBUFS);
    }
306     IF_ENQUEUE(ifq, m);
307     sc->sc_if.if_lastchange = time;
308     if (sc->sc_ttyp->t_outq.c_cc == 0)
309         slstart(sc->sc_ttyp);
310     splx(s);
311     return (0);
312 }
```
if_sl.c

Figure 5.15 `sloutput` function.

259–289 The four arguments to `sloutput` are: `ifp`, a pointer to the SLIP `ifnet` structure (in this case an `sl_softc` structure); `m`, a pointer to the packet to be queued for output; `dst`, the next-hop destination for the packet; and `rtp`, a pointer to a route entry. The fourth argument is not used by `sloutput`, but it is required since `sloutput` must match the prototype for the `if_output` function in the `ifnet` structure.

`sloutput` ensures that `dst` is an IP address, that the interface is connected to a TTY device, and that the TTY device is operating (i.e., the carrier is on or should be ignored). An error is returned immediately if any of these tests fail.

290–291 The SLIP interface maintains two queues of outgoing packets. The standard queue, `if_snd`, is selected by default.

292–295 If the outgoing packet contains an ICMP message and `SC_NOICMP` is set for the interface, the packet is discarded. This prevents a SLIP link from being overwhelmed by extraneous ICMP packets (e.g., ECHO packets) sent by a malicious user (Chapter 11).

The error code `ENETRESET` indicates that the packet was discarded because of a policy decision (versus a network failure). We'll see in Chapter 11 that the error is silently discarded unless the ICMP message was generated locally, in which case an error is returned to the process that tried to send the message.

Net/2 returned a 0 in this case. To a diagnostic tool such as `ping` or `traceroute` it would appear as if the packet disappeared since the output operation would report a successful completion.

In general, ICMP messages can be discarded. They are not required for correct operation, but discarding them makes troubleshooting more difficult and may lead to less than optimal routing decisions, poorer performance, and wasted network resources.

296–297 If the TOS field in the outgoing packet specifies low-delay service (`IPTOS_LOWDELAY`), the output queue is changed to `sc_fastq`.

RFC 1700 and RFC 1349 [Almquist 1992] specify the TOS settings for the standard protocols. Low-delay service is specified for Telnet, Rlogin, FTP (control), TFTP, SMTP (command phase), and DNS (UDP query). See Section 3.2 of Volume 1 for more details.

In previous BSD releases, the `ip_tos` was not set correctly by applications. The SLIP driver implemented TOS queueing by examining the transport headers contained within the IP packet. If it found TCP packets for the FTP (command), Telnet, or Rlogin ports, the packet was queued as if `IPTOS_LOWDELAY` was specified. Many routers continue this practice, since many implementations of these interactive services still do not set `ip_tos`.

298–312 The packet is now placed on the selected queue, the interface statistics are updated, and (if the TTY output queue is empty) sloutput calls slstart to initiate transmission of the packet.

SLIP increments if_oerrors if the interface queue is full; ether_output does not.

Unlike the Ethernet output function (ether_output), sloutput does not construct a data-link header for the outgoing packet. Since the only other system on a SLIP network is at the other end of the serial link, there is no need for hardware addresses or a protocol, such as ARP, to convert between IP addresses and hardware addresses. Protocol identifiers (such as the Ethernet *type* field) are also superfluous, since a SLIP link carries only IP packets.

slstart Function

In addition to the call by sloutput, the TTY device driver calls slstart when it drains its output queue and needs more bytes to transmit. The TTY subsystem manages its queues through a clist structure. In Figure 5.8 the output clist t_outq is shown below slstart and above the device's t_oproc function. slstart adds bytes to the queue, while t_oproc drains the queue and transmits the bytes.

The slstart function is shown in Figure 5.16.

318–358 When slstart is called, tp points to the device's tty structure. The body of slstart consists of a single for loop. If the output queue t_outq is not empty, slstart calls the output function for the device, t_oproc, which transmits as many bytes as the device will accept. If more than 100 bytes (SLIP_HIWAT) remain in the TTY output queue, slstart returns instead of adding another packet's worth of bytes to the queue. The output device generates an interrupt when it has transmitted all the bytes, and the TTY subsystem calls slstart when the output list is empty.

If the TTY output queue is empty, a packet is dequeued from sc_fastq or, if sc_fastq is empty, from the if_snd queue, thus transmitting all interactive packets before any other packets.

There are no standard SNMP variables to count packets queued according to the TOS fields. The XXX comment in line 353 indicates that the SLIP driver is counting low-delay packets in if_omcasts, *not* multicast packets.

359–383 If the SLIP interface is tapped by BPF, slstart makes a copy of the output packet before any header compression occurs. The copy is saved on the stack in the bpfbuf array .

384–388 If compression is enabled and the packet contains a TCP segment, sloutput calls sl_compress_tcp, which attempts to compress the packet. The resulting packet type is returned and logically ORed with the first byte in IP header (Section 29.13).

389–398 The compressed header is now copied into the BPF header, and the direction recorded as SLIPDIR_OUT. The completed BPF packet is passed to bpf_tap.

483–484 slstart returns if the for loop terminates.

if_sl.c

```
void
slstart(tp)
struct tty *tp;
{
    struct sl_softc *sc = (struct sl_softc *) tp->t_sc;
    struct mbuf *m;
    u_char *cp;
    struct ip *ip;
    int     s;
    struct mbuf *m2;
    u_char  bpfbuf[SLMTU + SLIP_HDRLEN];
    int     len;
    extern int cfreecount;

    for (;;) {
        /*
         * If there is more in the output queue, just send it now.
         * We are being called in lieu of ttstart and must do what
         * it would.
         */
        if (tp->t_outq.c_cc != 0) {
            (*tp->t_oproc) (tp);
            if (tp->t_outq.c_cc > SLIP_HIWAT)
                return;
        }
        /*
         * This happens briefly when the line shuts down.
         */
        if (sc == NULL)
            return;

        /*
         * Get a packet and send it to the interface.
         */
        s = splimp();
        IF_DEQUEUE(&sc->sc_fastq, m);
        if (m)
            sc->sc_if.if_omcasts++;     /* XXX */
        else
            IF_DEQUEUE(&sc->sc_if.if_snd, m);
        splx(s);
        if (m == NULL)
            return;

        /*
         * We do the header compression here rather than in sloutput
         * because the packets will be out of order if we are using TOS
         * queueing, and the connection id compression will get
         * munged when this happens.
         */
        if (sc->sc_bpf) {
            /*
             * We need to save the TCP/IP header before it's
             * compressed.  To avoid complicated code, we just
             * copy the entire packet into a stack buffer (since
                 * this is a serial line, packets should be short
                 * and/or the copy should be negligible cost compared
                 * to the packet transmission time).
                 */
                struct mbuf *m1 = m;
                u_char *cp = bpfbuf + SLIP_HDRLEN;

                len = 0;
                do {
                    int     mlen = m1->m_len;

                    bcopy(mtod(m1, caddr_t), cp, mlen);
                    cp += mlen;
                    len += mlen;
                } while (m1 = m1->m_next);
            }
            if ((ip = mtod(m, struct ip *))->ip_p == IPPROTO_TCP) {
                if (sc->sc_if.if_flags & SC_COMPRESS)
                    *mtod(m, u_char *) |= sl_compress_tcp(m, ip,
                                                          &sc->sc_comp, 1);
            }
            if (sc->sc_bpf) {
                /*
                 * Put the SLIP pseudo-"link header" in place.  The
                 * compressed header is now at the beginning of the
                 * mbuf.
                 */
                bpfbuf[SLX_DIR] = SLIPDIR_OUT;
                bcopy(mtod(m, caddr_t), &bpfbuf[SLX_CHDR], CHDR_LEN);
                bpf_tap(sc->sc_bpf, bpfbuf, len + SLIP_HDRLEN);
            }

                                  /* packet output code */

        }
    }
```
if_sl.c

Figure 5.16 `slstart` function: packet dequeueing.

The next section of `slstart` (Figure 5.17) discards packets if the system is low on memory, and implements a simple technique for discarding data generated by noise on the serial line. This is the code omitted from Figure 5.16.

399–409 If the system is low on clist structures, the packet is discarded and counted as a collision. By continuing the loop instead of returning, `slstart` quickly discards all remaining packets queued for output. Each iteration discards a packet, since the device still has too many bytes queued for output. Higher-level protocols must detect the lost packets and retransmit them.

410–418 If the TTY output queue is empty, the communication line may have been idle for a period of time and the receiver at the other end may have received extraneous data created by line noise. `slstart` places an extra SLIP END character in the output queue. A 0-length frame or a frame created by noise on the line should be discarded by the SLIP interface or IP protocol at the receiver.

if_sl.c
```
        sc->sc_if.if_lastchange = time;
        /*
         * If system is getting low on clists, just flush our
         * output queue (if the stuff was important, it'll get
         * retransmitted).
         */
        if (cfreecount < CLISTRESERVE + SLMTU) {
            m_freem(m);
            sc->sc_if.if_collisions++;
            continue;
        }
        /*
         * The extra FRAME_END will start up a new packet, and thus
         * will flush any accumulated garbage.  We do this whenever
         * the line may have been idle for some time.
         */
        if (tp->t_outq.c_cc == 0) {
            ++sc->sc_if.if_obytes;
            (void) putc(FRAME_END, &tp->t_outq);
        }
```
if_sl.c

Figure 5.17 `slstart` function: resource shortages and line noise.

Figure 5.18 illustrates this technique for discarding line noise and is attributed to Phil Karn in RFC 1055. In Figure 5.18, the second end-of-frame (END) is transmitted because the line was idle for a period of time. The invalid frame created by the noise and the END byte is discarded by the receiving system.

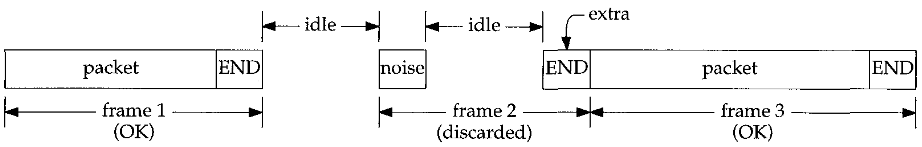


Figure 5.18 Karn's method for discarding noise on a SLIP line.

In Figure 5.19 there is no noise on the line and the 0-length frame is discarded by the receiving system.

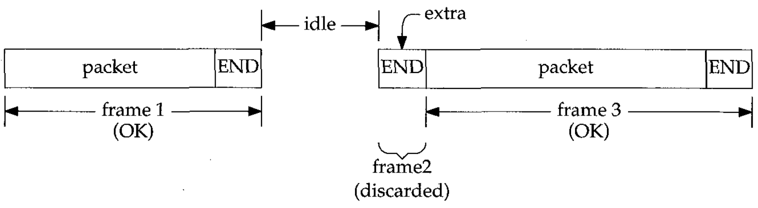


Figure 5.19 Karn's method with no noise.

The next section of `slstart` (Figure 5.20) transfers the data from an mbuf to the output queue for the TTY device.

if_sl.c

```
        while (m) {
            u_char *ep;

            cp = mtod(m, u_char *);
            ep = cp + m->m_len;
            while (cp < ep) {
                /*
                 * Find out how many bytes in the string we can
                 * handle without doing something special.
                 */
                u_char *bp = cp;

                while (cp < ep) {
                    switch (*cp++) {
                    case FRAME_ESCAPE:
                    case FRAME_END:
                        --cp;
                        goto out;
                    }
                }
              out:
                if (cp > bp) {
                    /*
                     * Put n characters at once
                     * into the tty output queue.
                     */
                    if (b_to_q((char *) bp, cp - bp,
                               &tp->t_outq))
                        break;
                    sc->sc_if.if_obytes += cp - bp;
                }
                /*
                 * If there are characters left in the mbuf,
                 * the first one must be special..
                 * Put it out in a different form.
                 */
                if (cp < ep) {
                    if (putc(FRAME_ESCAPE, &tp->t_outq))
                        break;
                    if (putc(*cp++ == FRAME_ESCAPE ?
                             TRANS_FRAME_ESCAPE : TRANS_FRAME_END,
                             &tp->t_outq)) {
                        (void) unputc(&tp->t_outq);
                        break;
                    }
                    sc->sc_if.if_obytes += 2;
                }
            }
            MFREE(m, m2);
            m = m2;
        }
```

if_sl.c

Figure 5.20 `slstart` function: packet transmission.

419–467 The outer `while` loop in this section is executed once for each mbuf in the chain. The middle `while` loop transfers the data from each mbuf to the output device. The inner `while` loop advances `cp` until it finds an END or ESC character. `b_to_q` transfers the bytes between `bp` and `cp`. END and ESC characters are escaped and queued with two calls to `putc`. This middle loop is repeated until all the bytes in the mbuf are passed to the TTY device's output queue. Figure 5.21 illustrates this process with an mbuf containing a SLIP END character and a SLIP ESC character.

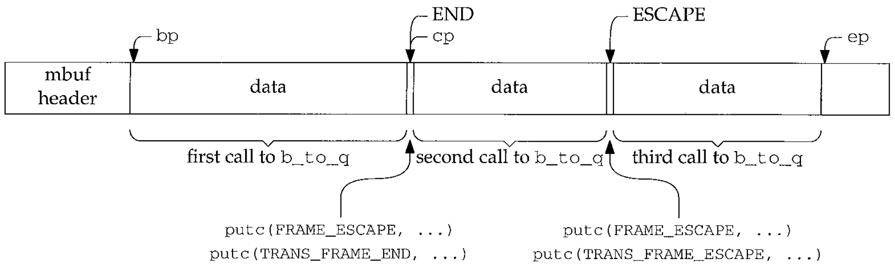


Figure 5.21 SLIP transmission of a single mbuf.

`bp` marks the beginning of the first section of the mbuf to transfer with `b_to_q`, and `cp` marks the end of the first section. `ep` marks the end of the data in the mbuf.

If `b_to_q` or `putc` fail (i.e., data cannot be queued on the TTY device), the `break` causes `slstart` to fall out of the inner `while` loop. The failure indicates that the kernel has run out of clist resources. After each mbuf is copied to the TTY device, or when an error occurs, the mbuf is released, `m` is advanced to the next mbuf in the chain, and the outer `while` loop continues until all the mbufs in the chain have been processed.

Figure 5.22 shows the processing done by `slstart` to complete the outgoing frame.

if_sl.c
```
468         if (putc(FRAME_END, &tp->t_outq)) {
469             /*
470              * Not enough room.  Remove a char to make room
471              * and end the packet normally.
472              * If you get many collisions (more than one or two
473              * a day) you probably do not have enough clists
474              * and you should increase "nclist" in param.c.
475              */
476             (void) unputc(&tp->t_outq);
477             (void) putc(FRAME_END, &tp->t_outq);
478             sc->sc_if.if_collisions++;
479         } else {
480             ++sc->sc_if.if_obytes;
481             sc->sc_if.if_opackets++;
482         }
```
if_sl.c

Figure 5.22 `slstart` function: end-of-frame processing.

468–482 Control reaches this code when the outer `while` loop has finished queueing the bytes on the output queue. The driver sends a SLIP END character, which terminates the frame.

If an error occurred while queueing the bytes, the outgoing frame is invalid and is detected by the receiving system because of an invalid checksum or length.

Whether or not the frame is terminated because of an error, if the END character does not fit on the output queue, the *last* character on the queue is discarded and `slstart` ends the frame. This guarantees that an END character is transmitted. The invalid frame is discarded at the destination.

SLIP Packet Loss

The SLIP interface provides a good example of a best-effort service. SLIP discards packets if the TTY is overloaded; it truncates packets if resources are unavailable after the packet transmission has started, and it inserts extraneous null packets to detect and discard line noise. In each of these cases, no error message is generated. SLIP depends on IP and the transport layers to detect damaged and missing packets.

On a router forwarding packets from a fast interface such as Ethernet to a low-speed SLIP line, a large percentage of packets are discarded if the sender does not recognize the bottleneck and respond by throttling back the data rate. In Section 25.11 we'll see how TCP detects and responds to this condition. Applications using a protocol without flow control, such as UDP, must recognize and respond to this condition on their own (Exercise 5.8).

SLIP Performance Considerations

The MTU of a SLIP frame (`SLMTU`), the clist high-water mark (`SLIP_HIWAT`), and SLIP's TOS queueing strategies are all designed to minimize the delay inherent in a slow serial link for interactive traffic.

1. A small MTU improves the delay for interactive data (such as keystrokes and echoes), but hurts the throughput for bulk data transfer. A large MTU improves bulk data throughput, but increases interactive delays. Another problem with SLIP links is that a single typed character is burdened with 40 bytes of TCP and IP header information, which increases the communication delay.

   The solution is to pick an MTU large enough to provide good interactive response time and decent bulk data throughput, and to compress TCP/IP headers to reduce the per-packet overhead. RFC 1144 [Jacobson 1990a] describes a compression scheme and the timing calculations that result in selecting an MTU of 296 for a typical 9600 bits/sec asynchronous SLIP link. We describe Compressed SLIP (CSLIP) in Section 29.13. Sections 2.10 and 7.2 of Volume 1 summarize the timing considerations and illustrate the delay on SLIP links.

2. If too many bytes are buffered in the clist (because `SLIP_HIWAT` is set too high), the TOS queueing will be thwarted as new interactive traffic waits behind the large amount of buffered data. If SLIP passes 1 byte at a time to the TTY driver

(because SLIP_HIWAT is set too low), the device calls slstart for each byte and the line is idle for a brief period of time after each byte is transferred. Setting SLIP_HIWAT to 100 minimizes the amount of data queued at the device and reduces the frequency at which the TTY subsystem must call slstart to approximately once every 100 characters.

3. As described, the SLIP driver provides TOS queueing by transmitting interactive traffic from the sc_fastq queue before other traffic on the standard interface queue, if_snd.

slclose Function

For completeness, we show the slclose function, which is called when the slattach program closes SLIP's TTY device and terminates the connection to the remote system.

if_sl.c

```
210 void
211 slclose(tp)
212 struct tty *tp;
213 {
214     struct sl_softc *sc;
215     int     s;

216     ttywflush(tp);
217     s = splimp();               /* actually, max(spltty, splnet) */
218     tp->t_line = 0;
219     sc = (struct sl_softc *) tp->t_sc;
220     if (sc != NULL) {
221         if_down(&sc->sc_if);
222         sc->sc_ttyp = NULL;
223         tp->t_sc = NULL;
224         MCLFREE((caddr_t) (sc->sc_ep - SLBUFSIZE));
225         sc->sc_ep = 0;
226         sc->sc_mp = 0;
227         sc->sc_buf = 0;
228     }
229     splx(s);
230 }
```

if_sl.c

Figure 5.23 slclose function.

210–230 tp points to the TTY device to be closed. slclose flushes any remaining data out to the serial device, blocks TTY and network processing, and resets the TTY to the default line discipline. If the TTY device is attached to a SLIP interface, the interface is shut down, the links between the two structures are severed, the mbuf cluster associated with the interface is released, and the pointers into the now-discarded cluster are reset. Finally, splx reenables the TTY and network interrupts.

`sltioctl` Function

Recall that a SLIP interface has two roles to play in the kernel:

- as a network interface, and
- as a TTY line discipline.

Figure 5.7 indicated that `slioctl` processes `ioctl` commands issued for a SLIP interface through a socket descriptor. In Section 4.4 we showed how `ifioctl` calls `slioctl`. We'll see a similar pattern for `ioctl` commands that we cover in later chapters.

Figure 5.7 also indicated that `sltioctl` processes `ioctl` commands issued for the TTY device associated with a SLIP network interface. The one command recognized by `sltioctl` is shown in Figure 5.24.

Command	Argument	Function	Description
`SLIOCGUNIT`	`int *`	`sltioctl`	return interface unit associated with the TTY device

Figure 5.24 `sltioctl` commands.

The `sltioctl` function is shown in Figure 5.25.

if_sl.c

```
236 int
237 sltioctl(tp, cmd, data, flag)
238 struct tty *tp;
239 int     cmd;
240 caddr_t data;
241 int     flag;
242 {
243     struct sl_softc *sc = (struct sl_softc *) tp->t_sc;

244     switch (cmd) {
245     case SLIOCGUNIT:
246         *(int *) data = sc->sc_if.if_unit;
247         break;

248     default:
249         return (-1);
250     }
251     return (0);
252 }
```

if_sl.c

Figure 5.25 `sltioctl` function.

236–252 The `t_sc` pointer in the `tty` structure points to the associated `sl_softc` structure. The unit number of the SLIP interface is copied from `if_unit` to `*data`, which is eventually returned to the process (Section 17.5).

`if_unit` is initialized by `slattach` when the system is initialized, and `t_sc` is initialized by `slopen` when the `slattach` program selects the SLIP line discipline for the TTY device. Since the mapping between a TTY device and a SLIP `sl_softc` structure is established at run time, a process can discover the interface structure selected by the SLIOCGUNIT command.

5.4 Loopback Interface

Any packets sent to the loopback interface (Figure 5.26) are immediately queued for input. The interface is implemented entirely in software.

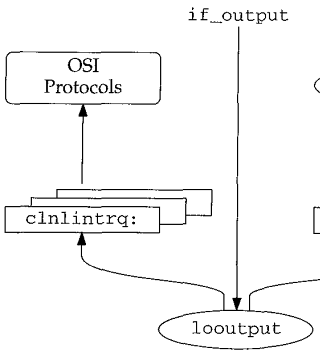


Figure 5.26 Loopback device driver.

looutput, the if_output function for the loopback interface, places outgoing packets on the input queue for the protocol specified by the packet's destination address.

We already saw that ether_output may call looutput to queue a copy of an outgoing broadcast packet when the device has set IFF_SIMPLEX. In Chapter 12, we'll see that multicast packets may be also be looped back in this way. looutput is shown in Figure 5.27.

if_loop.c
```
int
looutput(ifp, m, dst, rt)
struct ifnet *ifp;
struct mbuf *m;
struct sockaddr *dst;
struct rtentry *rt;
{
    int     s, isr;
    struct ifqueue *ifq = 0;

    if ((m->m_flags & M_PKTHDR) == 0)
        panic("looutput no HDR");
    ifp->if_lastchange = time;
    if (loif.if_bpf) {
        /*
         * We need to prepend the address family as
         * a four byte field.  Cons up a dummy header
         * to pacify bpf.  This is safe because bpf
         * will only read from the mbuf (i.e., it won't
         * try to free it or keep a pointer a to it).
         */
        struct mbuf m0;
        u_int   af = dst->sa_family;

        m0.m_next = m;
        m0.m_len = 4;
        m0.m_data = (char *) &af;

        bpf_mtap(loif.if_bpf, &m0);
    }
    m->m_pkthdr.rcvif = ifp;

    if (rt && rt->rt_flags & (RTF_REJECT | RTF_BLACKHOLE)) {
        m_freem(m);
        return (rt->rt_flags & RTF_BLACKHOLE ? 0 :
                rt->rt_flags & RTF_HOST ? EHOSTUNREACH : ENETUNREACH);
    }
    ifp->if_opackets++;
    ifp->if_obytes += m->m_pkthdr.len;
    switch (dst->sa_family) {
    case AF_INET:
        ifq = &ipintrq;
        isr = NETISR_IP;
        break;

    case AF_ISO:
        ifq = &clnlintrq;
        isr = NETISR_ISO;
        break;

    default:
        printf("lo%d: can't handle af%d\n", ifp->if_unit,
               dst->sa_family);
        m_freem(m);
        return (EAFNOSUPPORT);
    }
    s = splimp();
    if (IF_QFULL(ifq)) {
        IF_DROP(ifq);
        m_freem(m);
        splx(s);
        return (ENOBUFS);
    }
    IF_ENQUEUE(ifq, m);
    schednetisr(isr);
    ifp->if_ipackets++;
    ifp->if_ibytes += m->m_pkthdr.len;
    splx(s);
    return (0);
}
```
if_loop.c

Figure 5.27 The looutput function.

57–68 The arguments to `looutput` are the same as those to `ether_output` since both are called indirectly through the `if_output` pointer in their `ifnet` structures: `ifp`, a pointer to the outgoing interface's `ifnet` structure; `m`, the packet to send; `dst`, the destination address of the packet; and `rt`, routing information. If the first mbuf on the chain does not contain a packet, `looutput` calls `panic`.

Figure 5.28 shows the logical layout for a BPF loopback packet.

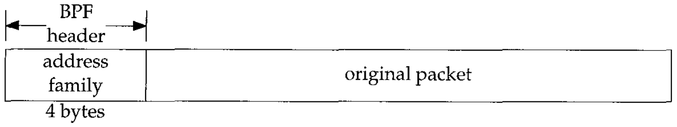


Figure 5.28 BPF loopback packet: logical format.

69–83 The driver constructs the BPF loopback packet in `m0` on the stack and connects `m0` to the mbuf chain containing the original packet. Note the unusual declaration of `m0`. It is an *mbuf*, not a pointer to an mbuf. `m_data` in `m0` points to `af`, which is also allocated on the stack. Figure 5.29 shows this arrangement.

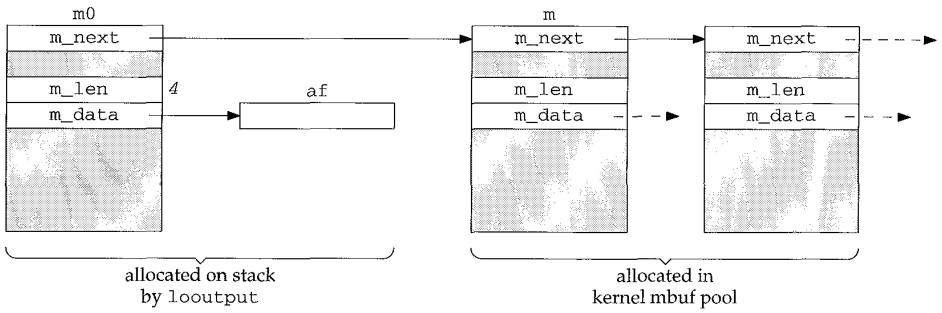


Figure 5.29 BPF loopback packet: mbuf format.

`looutput` copies the destination's address family into `af` and passes the new mbuf chain to `bpf_mtap`, which processes the packet. Contrast this to `bpf_tap`, which accepts the packet in a single contiguous buffer not in an mbuf chain. As the comment indicates, BPF never releases mbufs in a chain, so it is safe to pass `m0` (which points to an mbuf on the stack) to `bpf_mtap`.

84–89 The remainder of `looutput` contains *input* processing for the packet. Even though this is an output function, the packet is being looped back to appear as input. First, `m->m_pkthdr.rcvif` is set to point to the receiving interface. If the caller provided a routing entry, `looutput` checks to see if it indicates that the packet should be rejected (`RTF_REJECT`) or silently discarded (`RTF_BLACKHOLE`). A black hole is implemented by discarding the mbuf and returning 0. It appears to the caller as if the packet has been transmitted. To reject a packet, `looutput` returns `EHOSTUNREACH` if the route is for a host and `ENETUNREACH` if the route is for a network.

The various `RTF_`*xxx* flags are described in Figure 18.25.

90–120 `looutput` then selects the appropriate protocol input queue and software interrupt by examining `sa_family` in the packet's destination address. It then queues recognized packets and schedules a software interrupt with `schednetisr`.

5.5 Summary

We described the two remaining interfaces to which we refer throughout the text: `sl0`, a SLIP interface, and `lo0`, the standard loopback interface.

We showed the relationship between the SLIP interface and the SLIP line discipline, described the SLIP encapsulation method, and discussed TOS processing for interactive traffic and other performance considerations for the SLIP driver.

We showed how the loopback interface demultiplexes outgoing packets based on their destination address and places the packet on the appropriate input queue.

Exercises

5.1 Why does the loopback interface not have an input function?

5.2 Why do you think `mo` is allocated on the stack in Figure 5.27?

5.3 Perform an analysis of SLIP characteristics for a 19,200 bps serial line. Should the SLIP MTU be changed for this line?

5.4 Derive a formula to select a SLIP MTU based on the speed of the serial line.

5.5 What happens if a packet is too large to fit in SLIP's input buffer?

5.6 An earlier version of `slinput` did not set `SC_ERROR` when a packet overflowed the input buffer. How would the error be detected in this case?

5.7 In Figure 4.31 `le` is initialized by indexing the `le_softc` array with `ifp->if_unit`. Can you think of another method for initializing `le`?

5.8 How can a UDP application recognize when its packets are being discarded because of a bottleneck in the network?

6

IP Addressing

6.1 Introduction

This chapter describes how Net/3 manages IP addressing information. We start with the `in_ifaddr` and `sockaddr_in` structures, which are based on the generic `ifaddr` and `sockaddr` structures.

The remainder of the chapter covers IP address assignment and several utility functions that search the interface data structures and manipulate IP addresses.

IP Addresses

Although we assume that readers are familiar with the basic Internet addressing system, several issues are worth pointing out.

In the IP model, it is the network interfaces on a system (a host or a router) that are assigned addresses, not the system itself. In the case of a system with multiple interfaces, the system is *multihomed* and has more than one IP address. A router is, by definition, multihomed. As we'll see, this architectural feature has several subtle ramifications.

Five classes of IP addresses are defined. Class A, B, and C addresses support *unicast* communication. Class D addresses support IP *multicasting*. In a multicast communication, a single source sends a datagram to multiple destinations. Class D addresses and multicasting protocols are described in Chapter 12. Class E addresses are experimental. Packets received with class E addresses are discarded by hosts that aren't participating in the experiment.

It is important that we emphasize the difference between *IP multicasting* and *hardware multicasting*. Hardware multicasting is a feature of the data-link hardware used to transmit packets to multiple hardware interfaces. Some network hardware, such as Ethernet, supports data-link multicasting. Other hardware may not.

IP multicasting is a software feature implemented in IP systems to transmit packets to multiple IP addresses that may be located throughout the internet.

We assume that the reader is familiar with subnetting of IP networks (RFC 950 [Mogul and Postel 1985] and Chapter 3 of Volume 1). We'll see that each network interface has an associated subnet mask, which is critical in determining if a packet has reached its final destination or if it needs to be forwarded. In general, when we refer to the network portion of an IP address we are including any subnet that may defined. When we need to differentiate between the network and the subnet, we do so explicitly.

The loopback network, 127.0.0.0, is a special class A network. Addresses of this form must never appear outside of a host. Packets sent to this network are looped back and received by the host.

RFC 1122 requires that all addresses within the loopback network be handled correctly. Since the loopback interface must be assigned an address, many systems select 127.0.0.1 as the loopback address. If the system is not configured correctly, addresses such as 127.0.0.2 may not be routed to the loopback interface but instead may be transmitted on an attached network, which is prohibited. Some systems may correctly route the packet to the loopback interface where it is dropped since the destination address does not match the configured address: 127.0.0.1.

Figure 18.2 shows a Net/3 system configured to reject packets sent to a loopback address other than 127.0.0.1.

Typographical Conventions for IP Addresses

We usually display IP addresses in *dotted-decimal* notation. Figure 6.1 lists the range of IP address for each address class.

Class	Range	Type
A	**0**.0.0.0 to **127**.255.255.255	unicast
B	**128**.0.0.0 to **191**.255.255.255	
C	**192**.0.0.0 to **223**.255.255.255	
D	**224**.0.0.0 to **239**.255.255.255	multicast
E	**240**.0.0.0 to **247**.255.255.255	experimental

Figure 6.1 Ranges for different classes of IP addresses.

For some of our examples, the subnet field is not aligned with a byte boundary (i.e., a network/subnet/host division of 16/11/5 in a class B network). It can be difficult to identify the portions of such address from the dotted-decimal notation so we'll also use block diagrams to illustrate the contents of IP addresses. We'll show each address with three parts: network, subnet, and host. The shading of each part indicates its contents. Figure 6.2 illustrates both the block notation and the dotted-decimal notation using the Ethernet interface of the host sun from our sample network (Section 1.14).

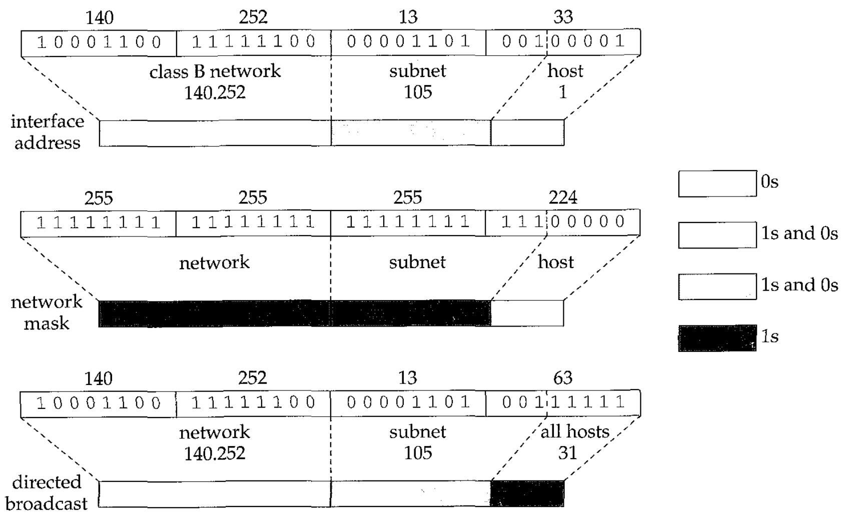


Figure 6.2 Alternate IP address notations.

When a portion of the address is not all 0s or all 1s, we use the two intermediate shades. We have two types of intermediate shades so we can distinguish network and subnet portions or to show combinations of address as in Figure 6.31.

Hosts and Routers

Systems on an internet can generally be divided into two types: *hosts* and *routers*. A host usually has a single network interface and is either the source or destination for an IP packet. A router has multiple network interfaces and forwards packets from one network to the next as the packet moves toward its destination. To perform this function, routers exchange information about the network topology using a variety of specialized routing protocols. IP routing issues are complex, and they are discussed starting in Chapter 18.

A system with multiple network interfaces is still called a *host* if it does not route packets between its network interfaces. A system may be both a host and a router. This is often the case when a router provides transport-level services such as Telnet access for configuration, or SNMP for network management. When the distinction between a host and router is unimportant, we use the term *system*.

Careless configuration of a router can disrupt the normal operation of a network, so RFC 1122 states that a system must default to operate as a host and must be explicitly configured by an administrator to operate as a router. This purposely discourages administrators from operating general-purpose host computers as routers without careful consideration. In Net/3, a system acts as a router if the global integer `ipforwarding` is nonzero and as a host if `ipforwarding` is 0 (the default).

A router is often called a *gateway* in Net/3, although the term *gateway* is now more often associated with a system that provides application-level routing, such as an electronic mail gateway, and not one that forwards IP packets. We use the term *router* and assume that `ipforwarding` is nonzero in this book. We have also included all code conditionally included when `GATEWAY` is defined during compilation of the Net/3 kernel, which defines `ipforwarding` to be 1.

6.2 Code Introduction

The two headers and two C files listed in Figure 6.3 contain the structure definitions and utility functions described in this chapter.

File	Description
`netinet/in.h`	Internet address definitions
`netinet/in_var.h`	Internet interface definitions
`netinet/in.c`	Internet initialization and utility functions
`netinet/if.c`	Internet interface utility functions

Figure 6.3 Files discussed in this chapter.

Global Variables

The two global variables introduced in this chapter are listed in Figure 6.4.

Variable	Datatype	Description
`in_ifaddr`	`struct in_ifaddr *`	head of `in_ifaddr` structure list
`in_interfaces`	`int`	number of IP capable interfaces

Figure 6.4 Global variables introduced in this chapter.

6.3 Interface and Address Summary

A sample configuration of all the interface and address structures described in this chapter is illustrated in Figure 6.5.

Figure 6.5 shows our three example interfaces: the Ethernet interface, the SLIP interface, and the loopback interface. All have a link-level address as the first node in their address list. The Ethernet interface is shown with two IP addresses, the SLIP interface with one IP address, and the loopback interface has an IP address and an OSI address.

Note that all the IP addresses are linked into the `in_ifaddr` list and all the link-level addresses can be accessed from the `ifnet_addrs` array.

The `ifa_ifp` pointers within each `ifaddr` structure have been omitted from Figure 6.5 for clarity. The pointers refer back to the `ifnet` structure that heads the list containing the `ifaddr` structure.

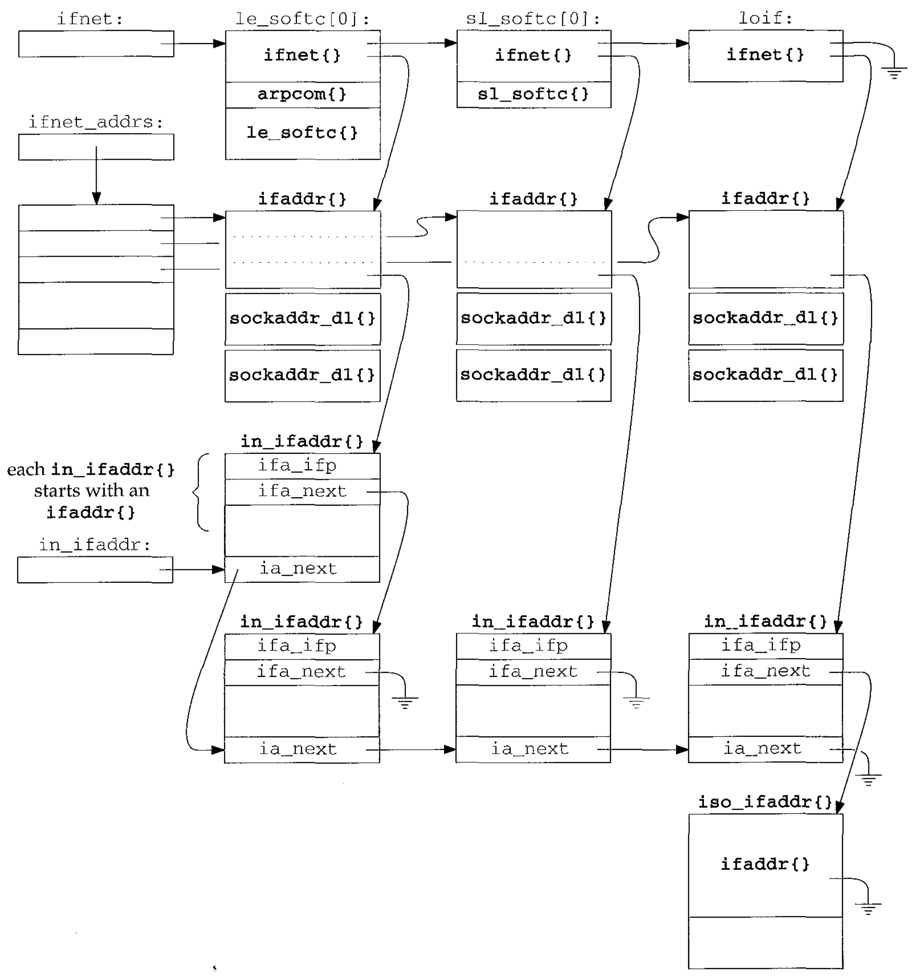


Figure 6.5 Interface and address data structures.

The following sections describe the data structures contained in Figure 6.5 and the IP-specific `ioctl` commands that examine and modify the structures.

6.4 `sockaddr_in` Structure

We discussed the generic sockaddr and ifaddr structures in Chapter 3. Now we show the structures specialized for IP: sockaddr_in and in_ifaddr. Addresses in the Internet domain are held in a sockaddr_in structure:

in.h
```
 68 struct in_addr {
 69     u_long  s_addr;              /* 32-bit IP address, net byte order */
 70 };

106 struct sockaddr_in {
107     u_char  sin_len;             /* sizeof (struct sockaddr_in) = 16 */
108     u_char  sin_family;          /* AF_INET */
109     u_short sin_port;            /* 16-bit port number, net byte order */
110     struct in_addr sin_addr;
111     char    sin_zero[8];         /* unused */
112 };
```
in.h

Figure 6.6 sockaddr_in structure.

68–70 Net/3 stores 32-bit Internet addresses in network byte order in an in_addr structure for historical reasons. The structure has a single member, s_addr, which contains the address. That organization is kept in Net/3 even though it is superfluous and clutters the code.

106–112 sin_len is always 16 (the size of the sockaddr_in structure) and sin_family is AF_INET. sin_port is a 16-bit value in network (not host) byte order used to demultiplex transport-level messages. sin_addr specifies a 32-bit Internet address.

Figure 6.6 shows that the sin_port, sin_addr, and sin_zero members of sockaddr_in overlay the sa_data member of sockaddr. sin_zero is unused in the Internet domain but must consist of all 0 bytes (Section 22.7). It pads the sockaddr_in structure to the length of a sockaddr structure.

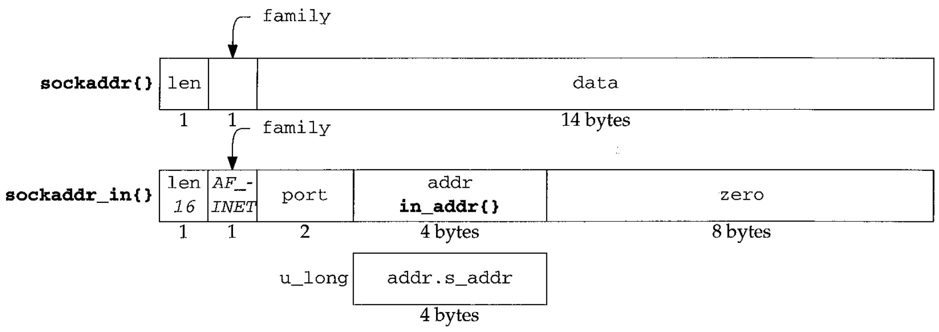


Figure 6.7 The organization of a sockaddr_in structure (sin_ omitted).

Usually, when an Internet addresses is stored in a u_long it is in host byte order to facilitate comparisons and bit operations on the address. s_addr within the in_addr structure (Figure 6.7) is a notable exception.

6.5 `in_ifaddr` Structure

Figure 6.8 shows the interface address structure defined for the Internet protocols. For each IP address assigned to an interface, an `in_ifaddr` structure is allocated and added to the interface address list and to the global list of IP addresses (Figure 6.5).

in_var.h

```
41 struct in_ifaddr {
42         struct  ifaddr ia_ifa;          /* protocol-independent info    */
43 #define ia_ifp         ia_ifa.ifa_ifp
44 #define ia_flags       ia_ifa.ifa_flags
45         struct  in_ifaddr *ia_next;     /* next internet addresses list */
46         u_long  ia_net;                 /* network number of interface  */
47         u_long  ia_netmask;             /* mask of net part             */
48         u_long  ia_subnet;              /* subnet number, including net */
49         u_long  ia_subnetmask;          /* mask of subnet part          */
50         struct  in_addr ia_netbroadcast; /* to recognize net broadcasts  */
51         struct  sockaddr_in ia_addr;    /* space for interface name     */
52         struct  sockaddr_in ia_dstaddr; /* space for broadcast addr     */
53 #define ia_broadaddr   ia_dstaddr
54         struct  sockaddr_in ia_sockmask; /* space for general netmask    */
55         struct  in_multi *ia_multiaddrs; /* list of multicast addresses  */
56 };
```

in_var.h

Figure 6.8 The `in_ifaddr` structure.

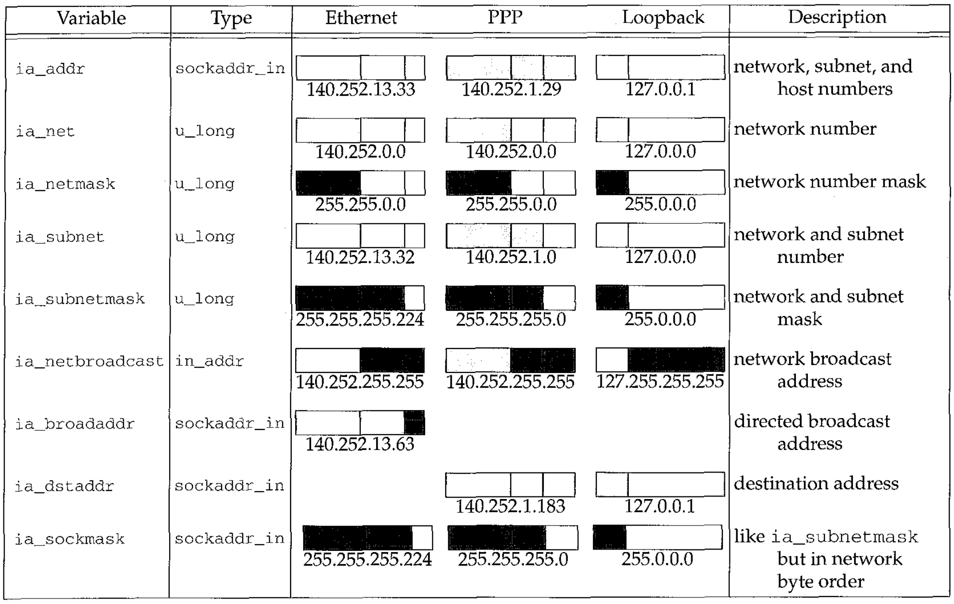
41–45 `in_ifaddr` starts with the generic interface address structure, `ia_ifa`, followed by the IP-specific members. The `ifaddr` structure was shown in Figure 3.15. The two macros, `ia_ifp` and `ia_flags`, simplify access to the interface pointer and interface address flags stored in the generic `ifaddr` structure. `ia_next` maintains a linked list of all Internet addresses that have been assigned to any interface. This list is independent of the list of link-level `ifaddr` structures associated with each interface and is accessed through the global list `in_ifaddr`.

46–54 The remaining members (other than `ia_multiaddrs`) are included in Figure 6.9, which shows the values for the three interfaces on `sun` from our example class B network. The addresses stored as `u_long` variables are kept in host byte order; the `in_addr` and `sockaddr_in` variables are in network byte order. `sun` has a PPP interface, but the information shown in this table is the same for a PPP interface or for a SLIP interface.

55–56 The last member of the `in_ifaddr` structure points to a list of `in_multi` structures (Section 12.6), each of which contains an IP multicast address associated with the interface.

6.6 Address Assignment

In Chapter 4 we showed the initialization of the interface structures when they are recognized at system initialization time. Before the Internet protocols can communicate through the interfaces, they must be assigned an IP address. Once the Net/3 kernel is



Variable	Type	Ethernet	PPP	Loopback	Description
`ia_addr`	`sockaddr_in`	140.252.13.33	140.252.1.29	127.0.0.1	network, subnet, and host numbers
`ia_net`	`u_long`	140.252.0.0	140.252.0.0	127.0.0.0	network number
`ia_netmask`	`u_long`	255.255.0.0	255.255.0.0	255.0.0.0	network number mask
`ia_subnet`	`u_long`	140.252.13.32	140.252.1.0	127.0.0.0	network and subnet number
`ia_subnetmask`	`u_long`	255.255.255.224	255.255.255.0	255.0.0.0	network and subnet mask
`ia_netbroadcast`	`in_addr`	140.252.255.255	140.252.255.255	127.255.255.255	network broadcast address
`ia_broadaddr`	`sockaddr_in`	140.252.13.63			directed broadcast address
`ia_dstaddr`	`sockaddr_in`		140.252.1.183	127.0.0.1	destination address
`ia_sockmask`	`sockaddr_in`	255.255.255.224	255.255.255.0	255.0.0.0	like `ia_subnetmask` but in network byte order

Figure 6.9 Ethernet, PPP, and loopback `in_ifaddr` structures on `sun`.

running, the interfaces are configured by the `ifconfig` program, which issues configuration commands through the `ioctl` system call on a socket. This is normally done by the `/etc/netstart` shell script, which is executed when the system is bootstrapped.

Figure 6.10 shows the `ioctl` commands discussed in this chapter. The addresses associated with the commands must be from the same address family supported by the socket on which the commands are issued (i.e., you can't configure an OSI address through a UDP socket). For IP addresses, the `ioctl` commands are issued on a UDP socket.

Command	Argument	Function	Description
SIOCGIFADDR	`struct ifreq *`	`in_control`	get interface address
SIOCGIFNETMASK	`struct ifreq *`	`in_control`	get interface netmask
SIOCGIFDSTADDR	`struct ifreq *`	`in_control`	get interface destination address
SIOCGIFBRDADDR	`struct ifreq *`	`in_control`	get interface broadcast address
SIOCSIFADDR	`struct ifreq *`	`in_control`	set interface address
SIOCSIFNETMASK	`struct ifreq *`	`in_control`	set interface netmask
SIOCSIFDSTADDR	`struct ifreq *`	`in_control`	set interface destination address
SIOCSIFBRDADDR	`struct ifreq *`	`in_control`	set interface broadcast address
SIOCDIFADDR	`struct ifreq *`	`in_control`	delete interface address
SIOCAIFADDR	`struct in_aliasreq *`	`in_control`	add interface address

Figure 6.10 Interface `ioctl` commands.

The commands that get address information start with SIOCG, and the commands that set address information start with SIOCS. SIOC stands for *socket ioctl*, the G for *get*, and the S for *set*.

In Chapter 4 we looked at five *protocol-independent* ioctl commands. The commands in Figure 6.10 modify the addressing information associated with an interface. Since addresses are protocol-specific, the command processing is *protocol-dependent*. Figure 6.11 highlights the ioctl-related functions associated with these commands.

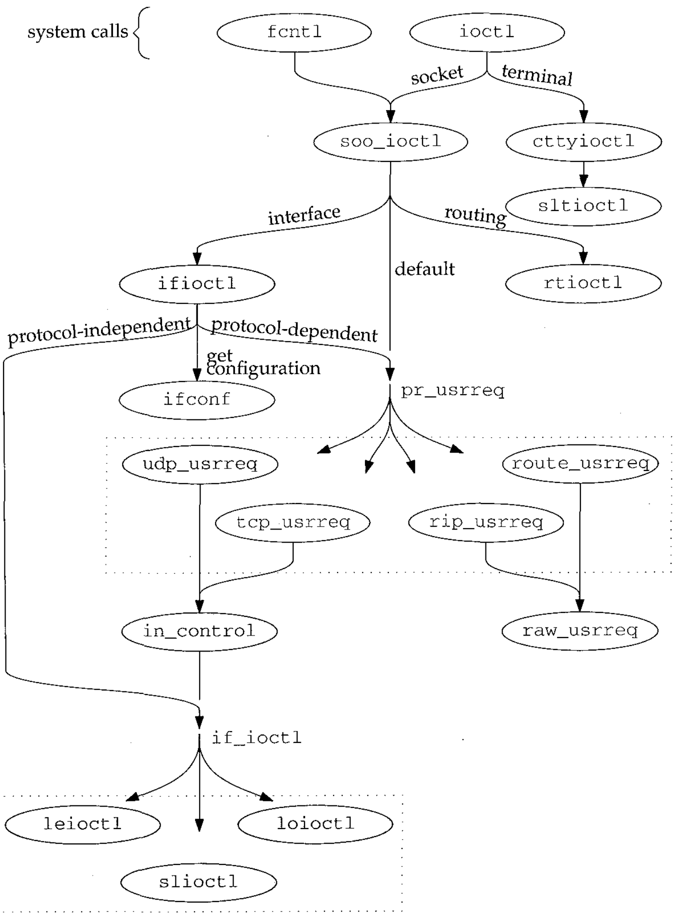


Figure 6.11 ioctl functions described in this chapter.

`ifioctl` Function

As shown in Figure 6.11, `ifioctl` passes protocol-dependent `ioctl` commands to the `pr_usrreq` function of the protocol associated with the socket. Control is passed to `udp_usrreq` and immediately to `in_control` where most of the processing occurs. If the same commands are issued on a TCP socket, control would also end up at `in_control`. Figure 6.12 repeats the `default` code from `ifioctl`, first shown in Figure 4.22.

if.c
```
447     default:
448         if (so->so_proto == 0)
449             return (EOPNOTSUPP);
450         return ((*so->so_proto->pr_usrreq) (so, PRU_CONTROL,
451                                             cmd, data, ifp));
452     }
453     return (0);
454 }
```
if.c

Figure 6.12 `ifioctl` function: protocol-specific commands.

447–454 The function passes all the relevant data for the `ioctl` commands listed in Figure 6.10 to the user-request function of the protocol associated with the socket on which the request was made. For a UDP socket, `udp_usrreq` is called. Section 23.10 describes the `udp_usrreq` function in detail. For now, we need to look only at the `PRU_CONTROL` code from `udp_usrreq`:

```
if (req == PRU_CONTROL)
    return (in_control(so, (int)m, (caddr_t)addr, (struct ifnet *)control));
```

`in_control` Function

Figure 6.11 shows that control can reach `in_control` through the `default` case in `soo_ioctl` or through the protocol-dependent case in `ifioctl`. In both cases, `udp_usrreq` calls `in_control` and returns whatever `in_control` returns. Figure 6.13 shows `in_control`.

132–145 `so` points to the socket on which the `ioctl` (specified by the second argument, `cmd`) was issued. The third argument, `data`, points to the data (second column of Figure 6.10) to be used or returned by the command. The last argument, `ifp`, is null (non-interface `ioctl` from `soo_ioctl`) or points to the interface named in the `ifreq` or `in_aliasreq` structures (interface `ioctl` from `ifioctl`). `in_control` initializes `ifa` and `ifra` to access `data` as an `ifreq` or as an `in_aliasreq` structure.

146–152 If `ifp` points to an `ifnet` structure, the `for` loop locates the *first* address on the Internet address list associated with the interface. If an address is found, `ia` points to its `in_ifaddr` structure, otherwise, `ia` is null.

If `ifp` is null, `cmd` will not match any of the cases in the first `switch` or any of the nondefault cases in the second `switch`. The `default` case in the second `switch` returns `EOPNOTSUPP` when `ifp` is null.

```
                                                                                in.c
132 in_control(so, cmd, data, ifp)
133 struct socket *so;
134 int     cmd;
135 caddr_t data;
136 struct ifnet *ifp;
137 {
138     struct ifreq *ifr = (struct ifreq *) data;
139     struct in_ifaddr *ia = 0;
140     struct ifaddr *ifa;
141     struct in_ifaddr *oia;
142     struct in_aliasreq *ifra = (struct in_aliasreq *) data;
143     struct sockaddr_in oldaddr;
144     int     error, hostIsNew, maskIsNew;
145     u_long  i;

146     /*
147      * Find address for this interface, if it exists.
148      */
149     if (ifp)
150         for (ia = in_ifaddr; ia; ia = ia->ia_next)
151             if (ia->ia_ifp == ifp)
152                 break;

153     switch (cmd) {

                        /* establish preconditions for commands */

218     }
219     switch (cmd) {

                                /* perform the commands */

326     default:
327         if (ifp == 0 || ifp->if_ioctl == 0)
328             return (EOPNOTSUPP);
329         return ((*ifp->if_ioctl) (ifp, cmd, data));
330     }
331     return (0);
332 }
                                                                                in.c
```

Figure 6.13 `in_control` function.

153–330 The first `switch` in `in_control` makes sure all the preconditions for each command are met before the second `switch` processes the command. The individual cases are described in the following sections.

If the `default` case is executed in the second `switch`, `ifp` points to an interface structure, and the interface has an `if_ioctl` function, then `in_control` passes the `ioctl` command to the interface for device-specific processing.

Net/3 does not define any interface commands that would be processed by the default case. But the driver for a particular device might define its own interface ioctl commands and they would be processed by this case.

331–332 We'll see that many of the cases within the switch statements return directly. If control falls through both switch statements, in_control returns 0. Several of the cases do break out of the second switch.

We look at the interface ioctl commands in the following order:

- assigning an address, network mask, or destination address;
- assigning a broadcast address;
- retrieving an address, network mask, destination address, or broadcast address;
- assigning multiple addresses to an interface; or
- deleting an address.

For each group of commands, we describe the precondition processing done in the first switch statement and then the command processing done in the second switch statement.

Preconditions: SIOCSIFADDR, SIOCSIFNETMASK, and SIOCSIFDSTADDR

Figure 6.14 shows the precondition testing for SIOCSIFADDR, SIOCSIFNETMASK, and SIOCSIFDSTADDR.

Superuser only

166–172 If the socket was not created by a superuser process, these commands are prohibited and in_control returns EPERM. If no interface is associated with the request, the kernel panics. The panic should never happen since ifioctl returns if it can't locate an interface (Figure 4.22).

The SS_PRIV flag is set by socreate (Figure 15.16) when a superuser process creates a socket. Because the test here is against the flag and not the effective user ID of the process, a set-user-ID root process can create a socket, and give up its superuser privileges, but still issue privileged ioctl commands.

Allocate structure

173–191 If ia is null, the command is requesting a new address. in_control allocates an in_ifaddr structure, clears it with bzero, and links it into the in_ifaddr list for the system and into the if_addrlist list for the interface.

Initialize structure

192–206 The next portion of code initializes the in_ifaddr structure. First the generic pointers in the ifaddr portion of the structure are initialized to point to the sockaddr_in structures in the in_ifaddr structure. The function also initializes the ia_sockmask and ia_broadaddr structures as necessary. Figure 6.15 illustrates the in_ifaddr structure after this initialization.

202–206 Finally, in_control establishes the back pointer from the in_ifaddr to the interface's ifnet structure.

Net/3 counts only nonloopback interfaces in in_interfaces.

in.c

```
    case SIOCSIFADDR:
    case SIOCSIFNETMASK:
    case SIOCSIFDSTADDR:
        if ((so->so_state & SS_PRIV) == 0)
            return (EPERM);

        if (ifp == 0)
            panic("in_control");
        if (ia == (struct in_ifaddr *) 0) {
            oia = (struct in_ifaddr *)
                malloc(sizeof *oia, M_IFADDR, M_WAITOK);
            if (oia == (struct in_ifaddr *) NULL)
                return (ENOBUFS);
            bzero((caddr_t) oia, sizeof *oia);
            if (ia = in_ifaddr) {
                for (; ia->ia_next; ia = ia->ia_next)
                    continue;
                ia->ia_next = oia;
            } else
                in_ifaddr = oia;
            ia = oia;
            if (ifa = ifp->if_addrlist) {
                for (; ifa->ifa_next; ifa = ifa->ifa_next)
                    continue;
                ifa->ifa_next = (struct ifaddr *) ia;
            } else
                ifp->if_addrlist = (struct ifaddr *) ia;

            ia->ia_ifa.ifa_addr = (struct sockaddr *) &ia->ia_addr;
            ia->ia_ifa.ifa_dstaddr
                = (struct sockaddr *) &ia->ia_dstaddr;
            ia->ia_ifa.ifa_netmask
                = (struct sockaddr *) &ia->ia_sockmask;
            ia->ia_sockmask.sin_len = 8;
            if (ifp->if_flags & IFF_BROADCAST) {
                ia->ia_broadaddr.sin_len = sizeof(ia->ia_addr);
                ia->ia_broadaddr.sin_family = AF_INET;
            }
            ia->ia_ifp = ifp;
            if (ifp != &loif)
                in_interfaces++;
        }
        break;
```

in.c

Figure 6.14 in_control function: address assignment.

Address Assignment: SIOCSIFADDR

The precondition code has ensured that ia points to an in_ifaddr structure to be modified by the SIOCSIFADDR command. Figure 6.16 shows the code executed by in_control in the second switch for this command.

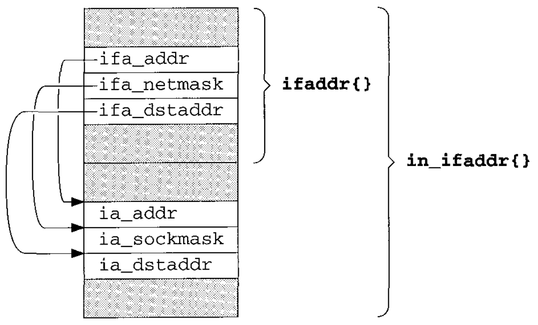


Figure 6.15 An `in_ifaddr` structure after initialization by `in_control`.

in.c
```
259     case SIOCSIFADDR:
260         return (in_ifinit(ifp, ia,
261                           (struct sockaddr_in *) &ifr->ifr_addr, 1));
```
in.c

Figure 6.16 `in_control` function: address assignment.

259–261 `in_ifinit` does all the work. The IP address included within the `ifreq` structure (`ifr_addr`) is passed to `in_ifinit`.

`in_ifinit` Function

The major steps in `in_ifinit` are:

- copy the address into the structure and inform the hardware of the change,
- discard any routes configured with the previous address,
- establish a subnet mask for the address,
- establish a default route to the attached network (or host), and
- join the all-hosts group on the interface.

The code is described in three parts, starting with Figure 6.17.

353–357 The four arguments to `in_ifinit` are: `ifp`, a pointer to the interface structure; `ia`, a pointer to the `in_ifaddr` structure to be changed; `sin`, a pointer to the requested IP address; and `scrub`, which indicates if existing routes for this interface should be discarded. `i` holds the IP address in host byte order.

Assign address and notify hardware

358–374 `in_ifinit` saves the previous address in `oldaddr` in case it must be restored when an error occurs. If the interface has an `if_ioctl` function defined, `in_control` calls it. The three functions `leioctl`, `slioctl`, and `loioctl` for the sample interfaces are described in the next section. The previous address is restored and `in_control` returns if an error occurs.

in.c

```
353 in_ifinit(ifp, ia, sin, scrub)
354 struct ifnet *ifp;
355 struct in_ifaddr *ia;
356 struct sockaddr_in *sin;
357 int     scrub;
358 {
359     u_long  i = ntohl(sin->sin_addr.s_addr);
360     struct sockaddr_in oldaddr;
361     int     s = splimp(), flags = RTF_UP, error, ether_output();

362     oldaddr = ia->ia_addr;
363     ia->ia_addr = *sin;
364     /*
365      * Give the interface a chance to initialize
366      * if this is its first address,
367      * and to validate the address if necessary.
368      */
369     if (ifp->if_ioctl &&
370         (error = (*ifp->if_ioctl) (ifp, SIOCSIFADDR, (caddr_t) ia))) {
371         splx(s);
372         ia->ia_addr = oldaddr;
373         return (error);
374     }
375     if (ifp->if_output == ether_output) {   /* XXX: Another Kludge */
376         ia->ia_ifa.ifa_rtrequest = arp_rtrequest;
377         ia->ia_ifa.ifa_flags |= RTF_CLONING;
378     }
379     splx(s);
380     if (scrub) {
381         ia->ia_ifa.ifa_addr = (struct sockaddr *) &oldaddr;
382         in_ifscrub(ifp, ia);
383         ia->ia_ifa.ifa_addr = (struct sockaddr *) &ia->ia_addr;
384     }
```

in.c

Figure 6.17 in_ifinit function: address assignment and route initialization.

Ethernet configuration

375–378 For Ethernet devices, arp_rtrequest is selected as the link-level routing function and the RTF_CLONING flag is set. arp_rtrequest is described in Section 21.13 and RTF_CLONING is described at the end of Section 19.4. As the XXX comment suggests, putting the code here avoids changing all the Ethernet drivers.

Discard previous routes

379–384 If the caller requests that existing routes be scrubbed, the previous address is reattached to ifa_addr while in_ifscrub locates and invalidates any routes based on the old address. After in_ifscrub returns, the new address is restored.

The section of in_ifinit shown in Figure 6.18 constructs the network and subnet masks.

in.c

```
385     if (IN_CLASSA(i))
386         ia->ia_netmask = IN_CLASSA_NET;
387     else if (IN_CLASSB(i))
388         ia->ia_netmask = IN_CLASSB_NET;
389     else
390         ia->ia_netmask = IN_CLASSC_NET;
391     /*
392      * The subnet mask usually includes at least the standard network part,
393      * but may be smaller in the case of supernetting.
394      * If it is set, we believe it.
395      */
396     if (ia->ia_subnetmask == 0) {
397         ia->ia_subnetmask = ia->ia_netmask;
398         ia->ia_sockmask.sin_addr.s_addr = htonl(ia->ia_subnetmask);
399     } else
400         ia->ia_netmask &= ia->ia_subnetmask;
401     ia->ia_net = i & ia->ia_netmask;
402     ia->ia_subnet = i & ia->ia_subnetmask;
403     in_socktrim(&ia->ia_sockmask);
```

in.c

Figure 6.18 `in_ifinit` function: network and subnet masks.

Construct network mask and default subnetmask

385–400 A tentative network mask is constructed in `ia_netmask` based on whether the address is a class A, class B, or class C address. If no subnetwork mask is associated with the address yet, `ia_subnetmask` and `ia_sockmask` are initialized to the tentative mask in `ia_netmask`.

If a subnet has been specified, `in_ifinit` logically ANDs the tentative netmask and the existing submask together to get a new network mask. This operation may clear some of the 1 bits in the tentative netmask (it can never set the 0 bits, since 0 logically ANDed with anything is 0). In this case, the network mask has fewer 1 bits than would be expected by considering the class of the address.

This is called *supernetting* and is described in RFC 1519 [Fuller et al. 1993]. A supernet is a grouping of several class A, class B, or class C networks. Supernetting is also discussed in Section 10.8 of Volume 1.

An interface is configured by default *without subnetting* (i.e., the network and subnetwork masks are the same). An explicit request (with `SIOCSIFNETMASK` or `SIOCAIFADDR`) is required to enable subnetting (or supernetting).

Construct network and subnetwork numbers

401–403 The network and subnetwork numbers are extracted from the new address by the network and subnet masks. The function `in_socktrim` sets the length of `in_sockmask` (which is a `sockaddr_in` structure) by locating the last byte that contains a 1 bit in the mask.

Figure 6.19 shows the last section of `in_ifinit`, which adds a route for the interface and joins the all-hosts multicast group.

in.c

```
404     /*
405      * Add route for the network.
406      */
407     ia->ia_ifa.ifa_metric = ifp->if_metric;
408     if (ifp->if_flags & IFF_BROADCAST) {
409         ia->ia_broadaddr.sin_addr.s_addr =
410             htonl(ia->ia_subnet | ~ia->ia_subnetmask);
411         ia->ia_netbroadcast.s_addr =
412             htonl(ia->ia_net | ~ia->ia_netmask);
413     } else if (ifp->if_flags & IFF_LOOPBACK) {
414         ia->ia_ifa.ifa_dstaddr = ia->ia_ifa.ifa_addr;
415         flags |= RTF_HOST;
416     } else if (ifp->if_flags & IFF_POINTOPOINT) {
417         if (ia->ia_dstaddr.sin_family != AF_INET)
418             return (0);
419         flags |= RTF_HOST;
420     }
421     if ((error = rtinit(&(ia->ia_ifa), (int) RTM_ADD, flags)) == 0)
422         ia->ia_flags |= IFA_ROUTE;
423     /*
424      * If the interface supports multicast, join the "all hosts"
425      * multicast group on that interface.
426      */
427     if (ifp->if_flags & IFF_MULTICAST) {
428         struct in_addr addr;

429         addr.s_addr = htonl(INADDR_ALLHOSTS_GROUP);
430         in_addmulti(&addr, ifp);
431     }
432     return (error);
433 }
```

in.c

Figure 6.19 `in_ifinit` function: routing and multicast groups.

Establish route for host or network

404–422 The next step is to create a route for the network specified by the new address. `in_ifinit` copies the routing metric from the interface to the `in_ifaddr` structure, constructs the broadcast addresses if the interface supports broadcasts, and forces the destination address to be the same as the assigned address for loopback interfaces. If a point-to-point interface does not yet have an IP address assigned to the other end of the link, `in_ifinit` returns before trying to establish a route for the invalid address.

`in_ifinit` initializes `flags` to `RTF_UP` and logically ORs in `RTF_HOST` for loopback and point-to-point interfaces. `rtinit` installs a route to the network (`RTF_HOST` not set) or host (`RTF_HOST` set) for the interface. If `rtinit` succeeds, the `IFA_ROUTE` flag in `ia_flags` is set to indicate that a route is installed for this address.

Join all-hosts group

423–433 Finally, a multicast capable interface must join the all-hosts multicast group when it is initialized. `in_addmulti` does the work and is described in Section 12.11.

Network Mask Assignment: SIOCSIFNETMASK

Figure 6.20 shows the processing for the network mask command.

in.c

```
262     case SIOCSIFNETMASK:
263         i = ifra->ifra_addr.sin_addr.s_addr;
264         ia->ia_subnetmask = ntohl(ia->ia_sockmask.sin_addr.s_addr = i);
265         break;
```

in.c

Figure 6.20 in_control function: network mask assignment.

262–265 in_control extracts the requested netmask from the ifreq structure and stores it in ia_sockmask in network byte order and in ia_subnetmask in host byte order.

Destination Address Assignment: SIOCSIFDSTADDR

For point-to-point interfaces, the address of the system on the other end of the link is specified by the SIOCSIFDSTADDR command. Figure 6.14 showed the precondition processing for the code shown in Figure 6.21.

in.c

```
236     case SIOCSIFDSTADDR:
237         if ((ifp->if_flags & IFF_POINTOPOINT) == 0)
238             return (EINVAL);
239         oldaddr = ia->ia_dstaddr;
240         ia->ia_dstaddr = *(struct sockaddr_in *) &ifr->ifr_dstaddr;
241         if (ifp->if_ioctl && (error = (*ifp->if_ioctl)
242                               (ifp, SIOCSIFDSTADDR, (caddr_t) ia))) {
243             ia->ia_dstaddr = oldaddr;
244             return (error);
245         }
246         if (ia->ia_flags & IFA_ROUTE) {
247             ia->ia_ifa.ifa_dstaddr = (struct sockaddr *) &oldaddr;
248             rtinit(&(ia->ia_ifa), (int) RTM_DELETE, RTF_HOST);
249             ia->ia_ifa.ifa_dstaddr =
250                 (struct sockaddr *) &ia->ia_dstaddr;
251             rtinit(&(ia->ia_ifa), (int) RTM_ADD, RTF_HOST | RTF_UP);
252         }
253         break;
```

in.c

Figure 6.21 in_control function: destination address assignment.

236–245 Only point-to-point networks have destination addresses, so in_control returns EINVAL for other networks. After saving the current destination address in oldaddr, the code sets the new address and informs the interface through the if_ioctl function. If an error occurs, the old address is restored.

246–253 If the address has a route previously associated with it, that route is deleted by the first call to rtinit and a new route to the new destination is installed by the second call to rtinit.

Retrieving Interface Information

Figure 6.22 shows the precondition processing for the SIOCSIFBRDADDR command as well as the ioctl commands that return interface information to the calling process.

in.c
```
207     case SIOCSIFBRDADDR:
208         if ((so->so_state & SS_PRIV) == 0)
209             return (EPERM);
210         /* FALLTHROUGH */

211     case SIOCGIFADDR:
212     case SIOCGIFNETMASK:
213     case SIOCGIFDSTADDR:
214     case SIOCGIFBRDADDR:
215         if (ia == (struct in_ifaddr *) 0)
216             return (EADDRNOTAVAIL);
217         break;
```
in.c

Figure 6.22 in_control function: preconditions.

207–217 The broadcast address may only be set through a socket created by a superuser process. The SIOCSIFBRDADDR command and the four SIOCG*xxx* commands work only when an address is already defined for the interface, in which case ia won't be null (ia was set by in_control, Figure 6.13). If ia is null, EADDRNOTAVAIL is returned.

The processing of these five commands (four *get* commands and one *set* command) is shown in Figure 6.23.

in.c
```
220     case SIOCGIFADDR:
221         *((struct sockaddr_in *) &ifr->ifr_addr) = ia->ia_addr;
222         break;

223     case SIOCGIFBRDADDR:
224         if ((ifp->if_flags & IFF_BROADCAST) == 0)
225             return (EINVAL);
226         *((struct sockaddr_in *) &ifr->ifr_dstaddr) = ia->ia_broadaddr;
227         break;

228     case SIOCGIFDSTADDR:
229         if ((ifp->if_flags & IFF_POINTOPOINT) == 0)
230             return (EINVAL);
231         *((struct sockaddr_in *) &ifr->ifr_dstaddr) = ia->ia_dstaddr;
232         break;

233     case SIOCGIFNETMASK:
234         *((struct sockaddr_in *) &ifr->ifr_addr) = ia->ia_sockmask;
235         break;

            /* processing for SIOCSIFDSTADDR command (Figure 6.21) */
```

```
254     case SIOCSIFBRDADDR:
255         if ((ifp->if_flags & IFF_BROADCAST) == 0)
256             return (EINVAL);
257         ia->ia_broadaddr = *(struct sockaddr_in *) &ifr->ifr_broadaddr;
258         break;
```
in.c

Figure 6.23 `in_control` function: processing.

220–235 The unicast address, broadcast address, destination address, or netmask are copied into the `ifreq` structure. A broadcast address is available only from a network interface that supports broadcasts, and a destination address is available only from a point-to-point interface.

254–258 The broadcast address is copied from the `ifreq` structure only when the interface supports broadcasts.

Multiple IP Addresses per Interface

The `SIOCG`*xxx* and `SIOCS`*xxx* commands operate only on the first IP address associated with an interface—the first address located by the loop at the start of `in_control` (Figure 6.25). To support multiple IP addresses per interface, the additional addresses must be assigned and configured with the `SIOCAIFADDR` command. In fact, `SIOCAIFADDR` can do everything the `SIOCG`*xxx* and `SIOCS`*xxx* commands do. The `ifconfig` program uses `SIOCAIFADDR` to configure all of the address information for an interface.

As noted earlier, having multiple addresses per interface can ease the transition when hosts or networks are renumbered. A fault-tolerant software system might use this feature to allow a backup system to assume the IP address of a failed system.

The `-alias` option to Net/3's `ifconfig` program passes information about the additional addresses to the kernel in an `in_aliasreq` structure, shown in Figure 6.24.

in_var.h
```
59 struct in_aliasreq {
60     char    ifra_name[IFNAMSIZ];    /* interface name, e.g. "en0" */
61     struct sockaddr_in ifra_addr;
62     struct sockaddr_in ifra_broadaddr;
63 #define ifra_dstaddr ifra_broadaddr
64     struct sockaddr_in ifra_mask;
65 };
```
in_var.h

Figure 6.24 `in_aliasreq` structure.

59–65 Notice that unlike the `ifreq` structure, there is no union defined within the `in_aliasreq` structure. With `SIOCAIFADDR`, the address, broadcast address, and mask can be specified in a single `ioctl` call.

`SIOCAIFADDR` adds a new address or changes the information associated with an existing address. `SIOCDIFADDR` deletes the `in_ifaddr` structure for the matching IP address. Figure 6.25 shows the precondition processing for the `SIOCAIFADDR` and `SIOCDIFADDR` commands, which assumes that the loop at the start of `in_control` (Figure 6.13) has set `ia` to point to the *first* IP address associated with the interface specified in `ifra_name` (if it exists).

```
                                                                    in.c
154     case SIOCAIFADDR:
155     case SIOCDIFADDR:
156         if (ifra->ifra_addr.sin_family == AF_INET)
157             for (oia = ia; ia; ia = ia->ia_next) {
158                 if (ia->ia_ifp == ifp &&
159                     ia->ia_addr.sin_addr.s_addr ==
160                     ifra->ifra_addr.sin_addr.s_addr)
161                     break;
162             }
163         if (cmd == SIOCDIFADDR && ia == 0)
164             return (EADDRNOTAVAIL);
165         /* FALLTHROUGH to Figure 6.14 */
                                                                    in.c
```

Figure 6.25 in_control function: adding and deleting addresses.

154–165 Because the SIOCDIFADDR code looks only at the first two members of *ifra, the code shown in Figure 6.25 works for SIOCAIFADDR (when ifra points to an in_aliasreq structure) and for SIOCDIFADDR (when ifra points to an ifreq structure). The first two members of the in_aliasreq and ifreq structures are identical.

For both commands, the for loop continues the search started by the loop at the start of in_control by looking for the in_ifaddr structure with the same IP address specified by ifra->ifra_addr. For the delete command, EADDRNOTAVAIL is returned if the address isn't found.

After the loop and the test for the delete command, control falls through to the code we described in Figure 6.14. For the add command, the code in Figure 6.14 allocates a new in_ifaddr structure if one was not found that matched the address in the in_aliasreq structure.

Additional IP Addresses: SIOCAIFADDR

At this point ia points to a new in_ifaddr structure or to an old in_ifaddr structure with an IP address that matched the address in the request. The SIOCAIFADDR processing is shown in Figure 6.26.

266–277 Since SIOCAIFADDR can create a new address or change the information associated with an existing address, the maskIsNew and hostIsNew flags keep track of what has changed so that routes can be updated if necessary at the end of the function.

By default, the code assumes that a new IP address is being assigned to the interface (hostIsNew starts at 1). If the length of the new address is 0, in_control copies the current address into the request and changes hostIsNew to 0. If the length is not 0 and the new address matches the old address, this request does not contain a new address and hostIsNew is set to 0.

278–284 If a netmask is specified in the request, any routes using the current address are discarded and in_control installs the new mask.

285–290 If the interface is a point-to-point interface and the request includes a new destination address, in_scrub discards any routes using the address, the new destination address is installed, and maskIsNew is set to 1 to force the call to in_ifinit, which reconfigures the interface.

in.c
```
266     case SIOCAIFADDR:
267         maskIsNew = 0;
268         hostIsNew = 1;
269         error = 0;
270         if (ia->ia_addr.sin_family == AF_INET) {
271             if (ifra->ifra_addr.sin_len == 0) {
272                 ifra->ifra_addr = ia->ia_addr;
273                 hostIsNew = 0;
274             } else if (ifra->ifra_addr.sin_addr.s_addr ==
275                        ia->ia_addr.sin_addr.s_addr)
276                 hostIsNew = 0;
277         }
278         if (ifra->ifra_mask.sin_len) {
279             in_ifscrub(ifp, ia);
280             ia->ia_sockmask = ifra->ifra_mask;
281             ia->ia_subnetmask =
282                 ntohl(ia->ia_sockmask.sin_addr.s_addr);
283             maskIsNew = 1;
284         }
285         if ((ifp->if_flags & IFF_POINTOPOINT) &&
286             (ifra->ifra_dstaddr.sin_family == AF_INET)) {
287             in_ifscrub(ifp, ia);
288             ia->ia_dstaddr = ifra->ifra_dstaddr;
289             maskIsNew = 1;      /* We lie; but the effect's the same */
290         }
291         if (ifra->ifra_addr.sin_family == AF_INET &&
292             (hostIsNew || maskIsNew))
293             error = in_ifinit(ifp, ia, &ifra->ifra_addr, 0);
294         if ((ifp->if_flags & IFF_BROADCAST) &&
295             (ifra->ifra_broadaddr.sin_family == AF_INET))
296             ia->ia_broadaddr = ifra->ifra_broadaddr;
297         return (error);
```
in.c

Figure 6.26 in_control function: SIOCAIFADDR processing.

291–297 If a new address has been configured or a new mask has been assigned, in_ifinit makes all the appropriate changes to support the new configuration (Figure 6.17). Note that the last argument to in_ifinit is 0. This indicates that it isn't necessary to scrub any routes since that has already been taken care of. Finally, the broadcast address is copied from the in_aliasreq structure if the interface supports broadcasts.

Deleting IP Addresses: SIOCDIFADDR

The SIOCDIFADDR command, which deletes IP addresses from an interface, is shown in Figure 6.27. Remember that ia points to the in_ifaddr structure to be deleted (i.e., the one that matched the request).

298–323 The precondition code arranged for ia to point to the address to be deleted. in_ifscrub deletes any routes associated with the address. The first if deletes the

in.c

```
298     case SIOCDIFADDR:
299         in_ifscrub(ifp, ia);
300         if ((ifa = ifp->if_addrlist) == (struct ifaddr *) ia)
301             /* ia is the first address in the list */
302             ifp->if_addrlist = ifa->ifa_next;
303         else {
304             /* ia is *not* the first address in the list */
305             while (ifa->ifa_next &&
306                    (ifa->ifa_next != (struct ifaddr *) ia))
307                 ifa = ifa->ifa_next;
308             if (ifa->ifa_next)
309                 ifa->ifa_next = ((struct ifaddr *) ia)->ifa_next;
310             else
311                 printf("Couldn't unlink inifaddr from ifp\n");
312         }
313         oia = ia;
314         if (oia == (ia = in_ifaddr))
315             in_ifaddr = ia->ia_next;
316         else {
317             while (ia->ia_next && (ia->ia_next != oia))
318                 ia = ia->ia_next;
319             if (ia->ia_next)
320                 ia->ia_next = oia->ia_next;
321             else
322                 printf("Didn't unlink inifadr from list\n");
323         }
324         IFAFREE((&oia->ia_ifa));
325         break;
```

in.c

Figure 6.27 in_control function: deleting addresses.

structure for the interface address list. The second if deletes the structure from the Internet address list (in_ifaddr).

324–325 IFAFREE only releases the structure when the reference count drops to 0.

The additional references would be from entries in the routing table.

6.7 Interface ioctl Processing

We now look at the specific ioctl processing done by each of our sample interfaces in the leioctl, slioctl, and loioctl functions when an address is assigned to the interface.

in_ifinit is called by the SIOCSIFADDR code in Figure 6.16 and by the SIOCAIFADDR code in Figure 6.26. in_ifinit always issues the SIOCSIFADDR command through the interface's if_ioctl function (Figure 6.17).

`leioctl` Function

Figure 4.31 showed `SIOCSIFFLAGS` command processing of the LANCE driver. Figure 6.28 shows the `SIOCSIFADDR` command processing.

if_le.c
```
614 leioctl(ifp, cmd, data)
615 struct ifnet *ifp;
616 int     cmd;
617 caddr_t data;
618 {
619     struct ifaddr *ifa = (struct ifaddr *) data;
620     struct le_softc *le = &le_softc[ifp->if_unit];
621     struct lereg1 *ler1 = le->sc_r1;
622     int     s = splimp(), error = 0;

623     switch (cmd) {
624     case SIOCSIFADDR:
625         ifp->if_flags |= IFF_UP;
626         switch (ifa->ifa_addr->sa_family) {
627         case AF_INET:
628             leinit(ifp->if_unit);    /* before arpwhohas */
629             ((struct arpcom *) ifp)->ac_ipaddr =
630                 IA_SIN(ifa)->sin_addr;
631             arpwhohas((struct arpcom *) ifp, &IA_SIN(ifa)->sin_addr);
632             break;
633         default:
634             leinit(ifp->if_unit);
635             break;
636         }
637         break;

                  /* SIOCSIFFLAGS command (Figure 4.31) */
        /* SIOCADDMULTI and SIOCDELMULTI commands (Figure 12.31) */

672     default:
673         error = EINVAL;
674     }
675     splx(s);
676     return (error);
677 }
```
if_le.c

Figure 6.28 `leioctl` function.

614–637 Before processing the command, `data` is converted to an `ifaddr` structure pointer and `ifp->if_unit` selects the appropriate `le_softc` structure for this request.

The interface is marked as up and the hardware is initialized by `leinit`. For Internet addresses, the IP address is stored in the `arpcom` structure and a *gratuitous ARP* for the address is issued. Gratuitous ARP is discussed in Section 21.5 and in Section 4.7 of Volume 1.

Unrecognized commands

672–677 `EINVAL` is returned for unrecognized commands.

sliotcl Function

The sliotcl function (Figure 6.29) processes the SIOCSIFADDR and SIOCSIFDSTADDR command for the SLIP device driver.

if_sl.c

```
653 int
654 slioctl(ifp, cmd, data)
655 struct ifnet *ifp;
656 int     cmd;
657 caddr_t data;
658 {
659     struct ifaddr *ifa = (struct ifaddr *) data;
660     struct ifreq *ifr;
661     int     s = splimp(), error = 0;

662     switch (cmd) {
663     case SIOCSIFADDR:
664         if (ifa->ifa_addr->sa_family == AF_INET)
665             ifp->if_flags |= IFF_UP;
666         else
667             error = EAFNOSUPPORT;
668         break;

669     case SIOCSIFDSTADDR:
670         if (ifa->ifa_addr->sa_family != AF_INET)
671             error = EAFNOSUPPORT;
672         break;

                /* SIOCADDMULTI and SIOCDELMULTI commands (Figure 12.29)*/

688     default:
689         error = EINVAL;
690     }
691     splx(s);
692     return (error);
693 }
```

if_sl.c

Figure 6.29 slioctl function: SIOCSIFADDR and SIOCSIFDSTADDR commands.

663–672 For both commands, EAFNOSUPPORT is returned if the address is not an IP address. The SIOCSIFADDR command enables IFF_UP.

Unrecognized commands

688–693 EINVAL is returned for unrecognized commands.

`loioctl` Function

The `loioctl` function and its implementation of the `SIOCSIFADDR` command is shown in Figure 6.30.

if_loop.c

```
135 int
136 loioctl(ifp, cmd, data)
137 struct ifnet *ifp;
138 int     cmd;
139 caddr_t data;
140 {
141     struct ifaddr *ifa;
142     struct ifreq *ifr;
143     int     error = 0;

144     switch (cmd) {
145     case SIOCSIFADDR:
146         ifp->if_flags |= IFF_UP;
147         ifa = (struct ifaddr *) data;
148         /*
149          * Everything else is done at a higher level.
150          */
151         break;


            /* SIOCADDMULTI and SIOCDELMULTI commands (Figure 12.30) */


167     default:
168         error = EINVAL;
169     }
170     return (error);
171 }
```

if_loop.c

Figure 6.30 `loioctl` function: `SIOCSIFADDR` command.

135–151 For Internet addresses, `loioctl` sets `IFF_UP` and returns immediately.

Unrecognized commands

167–171 `EINVAL` is returned for unrecognized commands.

Notice that for all three example drivers, assigning an address causes the interface to be marked as up (`IFF_UP`).

6.8 Internet Utility Functions

Figure 6.31 lists several functions that manipulate Internet addresses or that rely on the `ifnet` structures shown in Figure 6.5, usually to discover subnetting information that cannot be obtained from the 32-bit IP address alone. The implementation of these functions consists primarily of traversing data structures and manipulating bit masks. The reader can find these functions in `netinet/in.c`.

Function	Description
`in_netof`	Returns network and subnet portions of *in*. The host bits are set to 0. For class D addresses, returns the class D prefix bits and 0 bits for the multicast group. `u_long` **`in_netof`**`(struct in_addr` *in*);
`in_canforward`	Returns true if an IP packet addressed to *in* is eligible for forwarding. Class D and E addresses, loopback network addresses, and addresses with a network number of 0 must not be forwarded. `int` **`in_canforward`**`(struct in_addr` *in*);
`in_localaddr`	Returns true if the host *in* is located on a directly connected network. If the global variable `subnetsarelocal` is nonzero, then subnets of all directly connected networks are also considered local. `int` **`in_localaddr`**`(struct in_addr` *in*);
`in_broadcast`	Return true if *in* is a broadcast address associated with the interface pointed to by *ifp*. `int` **`in_broadcast`**`(struct in_addr` *in*, `struct ifnet` **ifp*);

Figure 6.31 Internet address functions.

Net/2 had a bug in `in_canforward` that permitted loopback addresses to be forwarded. Since most Net/2 systems are configured to recognize only a single loopback address, such as 127.0.0.1, Net/2 systems often forward other addresses in the loopback network (e.g., 127.0.0.2) along the default route.

A telnet to 127.0.0.2 may not do what you expect! (Exercise 6.6)

6.9 ifnet Utility Functions

Several functions search the data structures shown in Figure 6.5. The functions listed in Figure 6.32 accept addresses for any protocol family, since their argument is a pointer to a sockaddr structure, which contains the address family. Contrast this to the functions in Figure 6.31, each of which takes a 32-bit IP address as an argument. These functions are defined in net/if.c.

Function	Description
ifa_ifwithaddr	Search the ifnet list for an interface with a unicast or broadcast address of *addr*. Return a pointer to the matching ifaddr structure or a null pointer if no match is found. `struct ifaddr * **ifa_ifwithaddr**(struct sockaddr *addr);`
ifa_ifwithdstaddr	Search the ifnet list for the interface with a destination address of *addr*. Return a pointer to the matching ifaddr structure or a null pointer if no match is found. `struct ifaddr * **ifa_ifwithdstaddr**(struct sockaddr *addr);`
ifa_ifwithnet	Search the ifnet list for the address on the same network as *addr*. Return a pointer to the most specific matching ifaddr structure or a null pointer if no match is found. `struct ifaddr * **ifa_ifwithnet**(struct sockaddr *addr);`
ifa_ifwithaf	Search the ifnet list for the first address in the same address family as *addr*. Return a pointer to the matching ifaddr structure or a null pointer if no match is found. `struct ifaddr * **ifa_ifwithaf**(struct sockaddr *addr);`
ifaof_ifpforaddr	Search the address list of *ifp* for the address that matches *addr*. The order of preference is for an exact match, the destination address on a point-to-point link, an address on the same network, and finally an address in the same address family. Return a pointer to the matching ifaddr structure or a null pointer if no match is found. `struct ifaddr * **ifaof_ifpforaddr**(struct sockaddr *addr, struct ifnet *ifp);`
ifa_ifwithroute	Returns a pointer to the ifaddr structure for the appropriate local interface for the destination (dst), and gateway (gateway) specified. `struct ifaddr * **ifa_ifwithroute**(int flags, struct sockaddr *dst, struct sockaddr *gateway)`
ifunit	Return a pointer to the ifnet structure associated with *name*. `struct ifnet * **ifunit**(char *name);`

Figure 6.32 ifnet utility functions.

6.10 Summary

In this chapter we presented an overview of the IP addressing mechanisms and described interface address structures and protocol address structures that are specialized for IP: the in_ifaddr and sockaddr_in structures.

We described how interfaces are configured with IP-specific information through the ifconfig program and the ioctl interface commands.

Finally, we summarized several utility functions that manipulate IP addresses and search the interface data structures.

Exercises

6.1 Why do you think sin_addr in the sockaddr_in structure was originally defined as a structure?

6.2 ifunit("sl0") returns a pointer to which structure in Figure 6.5?

6.3 Why is the IP address duplicated in ac_ipaddr when it is already contained in an ifaddr structure on the interface's address list?

6.4 Why do you think IP interface addresses are accessed through a UDP socket and not a raw IP socket?

6.5 Why does in_socktrim change sin_len to match the length of the mask instead of using the standard length of a sockaddr_in structure?

6.6 What happens when the connection request segment from a telnet 127.0.0.2 command is erroneously forwarded by a Net/2 system and is eventually recognized and accepted by a system along the default route?

7

Domains and Protocols

7.1 Introduction

In this chapter we describe the Net/3 data structures that support the concurrent operation of multiple network protocols. We'll use the Internet protocols to illustrate the construction and initialization of these data structures at system initialization time. This chapter presents the necessary background material for our discussion of the IP protocol processing layer, which begins in Chapter 8.

Net/3 groups related protocols into a *domain,* and identifies each domain with a *protocol family* constant. Net/3 also groups protocols by the addressing method they employ. Recall from Figure 3.19 that address families also have identifying constants. Currently every protocol within a domain uses the same type of address and every address type is used by a single domain. As a result, a domain can be uniquely identified by its protocol family or address family constant. Figure 7.1 lists the protocols and constants that we discuss.

Protocol family	Address family	Protocol
`PF_INET`	`AF_INET`	Internet
`PF_OSI, PF_ISO`	`AF_OSI, AF_ISO`	OSI
`PF_LOCAL, PF_UNIX`	`AF_LOCAL, AF_UNIX`	local IPC (Unix)
`PF_ROUTE`	`AF_ROUTE`	routing tables
n/a	`AF_LINK`	link-level (e.g., Ethernet)

Figure 7.1 Common protocol and address family constants.

`PF_LOCAL` and `AF_LOCAL` are the primary identifiers for protocols that support communication between processes on the same host and are part of the POSIX.12 standard. Before Net/3, `PF_UNIX` and `AF_UNIX` identified these protocols. The `UNIX` constants remain for backward compatibility and are used by Net/3 and in this text.

The PF_UNIX domain supports interprocess communication on a single Unix host. See [Stevens 1990] for details. The PF_ROUTE domain supports communication between a process and the routing facilities in the kernel (Chapter 18). We reference the PF_OSI protocols occasionally, as some features of Net/3 exist only to support the OSI protocols, but do not discuss them in any detail. Most of our discussions are about the PF_INET protocols.

7.2 Code Introduction

Two headers and two C files are covered in this chapter. Figure 7.2 describes the four files.

File	Description
netinet/domain.h	domain structure definition
netinet/protosw.h	protosw structure definition
netinet/in_proto.c	IP domain and protosw structures
kern/uipc_domain.c	initialization and search functions

Figure 7.2 Files discussed in this chapter.

Global Variables

Figure 7.3 describes several important global data structures and system parameters that are described in this chapter and referenced throughout Net/3.

Variable	Datatype	Description
domains	struct domain *	linked list of domains
inetdomain	struct domain	domain structure for the Internet protocols
inetsw	struct protosw[]	array of protosw structures for the Internet protocols
max_linkhdr	int	see Figure 7.17
max_protohdr	int	see Figure 7.17
max_hdr	int	see Figure 7.17
max_datalen	int	see Figure 7.17

Figure 7.3 Global variables introduced in this chapter.

Statistics

No statistics are collected by the code described in this chapter, but Figure 7.4 shows the statistics table allocated and initialized by the ip_init function. The only way to look at this table is with a kernel debugger.

Variable	Datatype	Description
ip_ifmatrix	int[][]	two-dimensional array to count packets routed between any two interfaces

Figure 7.4 Statistics collected in this chapter.

7.3 domain Structure

A protocol domain is represented by a domain structure shown in Figure 7.5.

domain.h
```
42 struct domain {
43     int     dom_family;          /* AF_xxx */
44     char   *dom_name;
45     void    (*dom_init)          /* initialize domain data structures */
46             (void);
47     int     (*dom_externalize)   /* externalize access rights */
48             (struct mbuf *);
49     int     (*dom_dispose)       /* dispose of internalized rights */
50             (struct mbuf *);
51     struct protosw *dom_protosw, *dom_protoswNPROTOSW;
52     struct domain *dom_next;
53     int     (*dom_rtattach)      /* initialize routing table */
54             (void **, int);
55     int     dom_rtoffset;        /* an arg to rtattach, in bits */
56     int     dom_maxrtkey;        /* for routing layer */
57 };
```
domain.h

Figure 7.5 The domain structure definition.

42–57 dom_family is one of the address family constants (e.g., AF_INET) and specifies the addressing employed by the protocols in the domain. dom_name is a text name for the domain (e.g., "internet").

The dom_name member is not accessed by any part of the Net/3 kernel, but the fstat(1) program uses dom_name when it formats socket information.

dom_init points to the function that initializes the domain. dom_externalize and dom_dispose point to functions that manage access rights sent across a communication path within the domain. The Unix domain implements this feature to pass file descriptors between processes. The Internet domain does not implement access rights.

dom_protosw and dom_protoswNPROTOSW point to the start and end of an array of protosw structures. dom_next points to the next domain in a linked list of domains supported by the kernel. The linked list of all domains is accessed through the global pointer domains.

The next three members, dom_rtattach, dom_rtoffset, and dom_maxrtkey, hold routing information for the domain. They are described in Chapter 18.

Figure 7.6 shows an example domains list.

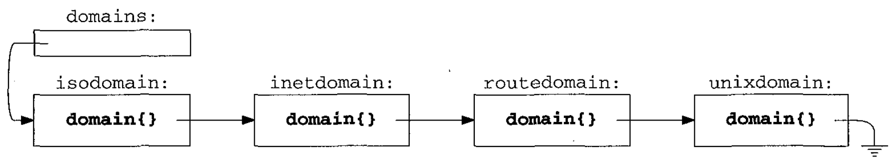


Figure 7.6 domains list.

7.4 protosw Structure

At compile time, Net/3 allocates and initializes a protosw structure for each protocol in the kernel and groups the structures for all protocols within a single domain into an array. Each domain structure references the appropriate array of protosw structures. A kernel may provide multiple interfaces to the same protocol by providing multiple protosw entries. For example, in Section 7.5 we describe three different entries for the IP protocol.

protosw.h
```
57 struct protosw {
58     short   pr_type;             /* see (Figure 7.8) */
59     struct domain *pr_domain;    /* domain protocol a member of */
60     short   pr_protocol;         /* protocol number */
61     short   pr_flags;            /* see Figure 7.9 */
62 /* protocol-protocol hooks */
63     void    (*pr_input) ();      /* input to protocol (from below) */
64     int     (*pr_output) ();     /* output to protocol (from above) */
65     void    (*pr_ctlinput) ();   /* control input (from below) */
66     int     (*pr_ctloutput) ();  /* control output (from above) */
67 /* user-protocol hook */
68     int     (*pr_usrreq) ();     /* user request from process */
69 /* utility hooks */
70     void    (*pr_init) ();       /* initialization hook */
71     void    (*pr_fasttimo) ();   /* fast timeout (200ms) */
72     void    (*pr_slowtimo) ();   /* slow timeout (500ms) */
73     void    (*pr_drain) ();      /* flush any excess space possible */
74     int     (*pr_sysctl) ();     /* sysctl for protocol */
75 };
```
protosw.h

Figure 7.7 The protosw structure definition.

57–61 The first four members in the structure identify and characterize the protocol. pr_type specifies the communication semantics of the protocol. Figure 7.8 lists the possible values for pr_type and the corresponding Internet protocols.

pr_type	Protocol semantics	Internet protocols
SOCK_STREAM	reliable bidirectional byte-stream service	TCP
SOCK_DGRAM	best-effort transport-level datagram service	UDP
SOCK_RAW	best-effort network-level datagram service	ICMP, IGMP, raw IP
SOCK_RDM	reliable datagram service (not implemented)	n/a
SOCK_SEQPACKET	reliable bidirectional record stream service	n/a

Figure 7.8 pr_type specifies the protocol's semantics.

pr_domain points to the associated domain structure, pr_protocol numbers the protocol within the domain, and pr_flags specifies additional characteristics of the protocol. Figure 7.9 lists the possible values for pr_flags.

pr_flags	Description
PR_ATOMIC	each process request maps to a single protocol request
PR_ADDR	protocol passes addresses with each datagram
PR_CONNREQUIRED	protocol is connection oriented
PR_WANTRCVD	notify protocol when a process receives data
PR_RIGHTS	protocol supports access rights

Figure 7.9 pr_flags values.

If PR_ADDR is supported by a protocol, PR_ATOMIC must also be supported. PR_ADDR and PR_CONNREQUIRED are mutually exclusive.

When PR_WANTRCVD is set, the socket layer notifies the protocol layer when it has passed data from the socket receive buffer to a process (i.e., when more space becomes available in the receive buffer).

PR_RIGHTS indicates that access right control messages can be passed across the connection. Access rights require additional support within the kernel to ensure proper cleanup if the receiving process does not consume the messages. Only the Unix domain supports access rights, where they are used to pass descriptors between processes.

Figure 7.10 shows the relationship between the protocol type, the protocol flags, and the protocol semantics.

	PR_			Record		Example	
pr_type	ADDR	ATOMIC	CONNREQUIRED	boundaries?	Reliable?	Internet	Other
SOCK_STREAM			•	none	•	TCP	SPP
SOCK_SEQPACKET			•	explicit	•		TP4
		•	•	implicit	•		SPP
SOCK_RDM		•	•	implicit	see text		RDP
SOCK_DGRAM	•	•		implicit		UDP	
SOCK_RAW	•	•		implicit		ICMP	

Figure 7.10 Protocol characteristics and examples.

Figure 7.10 does not include the PR_WANTRCVD or PR_RIGHTS flags. PR_WANTRCVD is always set for reliable connection-oriented protocols.

To understand communication semantics of a protosw entry in Net/3, we must consider the PR*xxx* flags and pr_type together. In Figure 7.10 we have included two columns ("Record boundaries?" and "Reliable?") to describe the additional semantics that are implicitly specified by pr_type. Figure 7.10 shows three types of reliable protocols:

- Connection-oriented byte stream protocols such as TCP and SPP (from the XNS protocol family). These protocols are identified by SOCK_STREAM.

- Connection-oriented stream protocols with record boundaries are specified by SOCK_SEQPACKET. Within this type of protocol, PR_ATOMIC indicates whether records are implicitly specified by each output request or are explicitly specified by setting the MSG_EOR flag on output. TP4 from the OSI protocol family requires explicit record boundaries, and SPP assumes implicit record boundaries.

  SPP supports both SOCK_STREAM and SOCK_SEQPACKET semantics.

- The third type of reliable protocol provides a connection-oriented service with implicit record boundaries and is specified by SOCK_RDM. RDP does not guarantee that records are received in the order that they are sent. RDP is described in [Partridge 1987] and specified by RFC 1151 [Partridge and Hinden 1990].

Two types of unreliable protocols are shown in Figure 7.10:

- A transport-level datagram protocol, such as UDP, which includes multiplexing and checksums, is specified by SOCK_DGRAM.
- A network-level datagram protocol, such as ICMP, which is specified by SOCK_RAW. In Net/3, only superuser processes may create a SOCK_RAW socket (Figure 15.18).

62–68 The next five members are function pointers providing access to the protocol from other protocols. pr_input handles incoming data from a lower-level protocol, pr_output handles outgoing data from a higher-level protocol, pr_ctlinput handles control information from below, and pr_ctloutput handles control information from above. pr_usrreq handles all communication requests from a process.

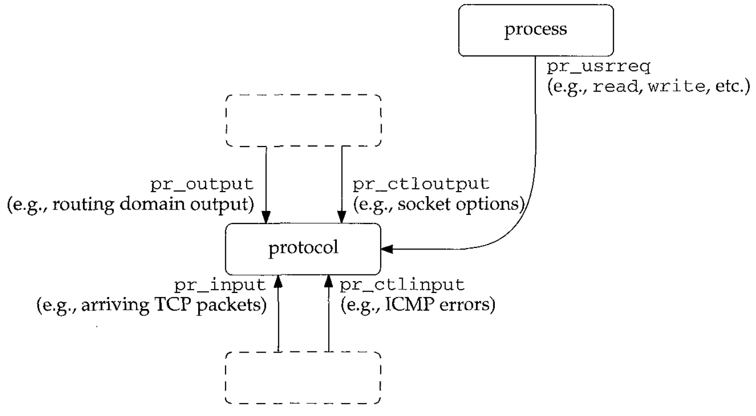


Figure 7.11 The five main entry points to a protocol.

69–75 The remaining five members are utility functions for the protocol. pr_init handles initialization. pr_fasttimo and pr_slowtimo are called every 200 ms and 500 ms respectively to perform periodic protocol functions, such as updating retransmission timers. pr_drain is called by m_reclaim when memory is in short supply (Figure 2.13). It is a request that the protocol release as much memory as possible. pr_sysctl provides an interface for the sysctl(8) command, a way to modify system-wide parameters, such as enabling packet forwarding or UDP checksum calculations.

7.5 IP domain and protosw Structures

The domain and protosw structures for all protocols are declared and initialized statically. For the Internet protocols, the inetsw array contains the protosw structures. Figure 7.12 summarizes the protocol information in the inetsw array. Figure 7.13 shows the definition of the array and the definition of the domain structure for the Internet protocols.

inetsw[]	pr_protocol	pr_type	Description	Acronym
0	*0*	*0*	Internet Protocol	IP
1	*IPPROTO_UDP*	*SOCK_DGRAM*	User Datagram Protocol	UDP
2	*IPPROTO_TCP*	*SOCK_STREAM*	Transmission Control Protocol	TCP
3	*IPPROTO_RAW*	*SOCK_RAW*	Internet Protocol (raw)	IP (raw)
4	*IPPROTO_ICMP*	*SOCK_RAW*	Internet Control Message Protocol	ICMP
5	*IPPROTO_IGMP*	*SOCK_RAW*	Internet Group Management Protocol	IGMP
6	*0*	*SOCK_RAW*	Internet Protocol (raw, default)	IP (raw)

Figure 7.12 Internet domain protocols.

39–77 Three protosw structures in the inetsw array provide access to IP. The first, inetsw[0], specifies administrative functions for IP and is accessed only by the kernel. The other two entries, inetsw[3] and inetsw[6], are identical except for their pr_protocol values and provide a *raw* interface to IP. inetsw[3] processes any packets that are received for unrecognized protocols. inetsw[6] is the default raw protocol, which the pffindproto function (Section 7.6) returns when no other match is found.

In releases before Net/3, packets transmitted through inetsw[3] did not have an IP header prepended. It was the responsibility of the process to construct the correct header. Packets transmitted through inetsw[6] had an IP header prepended by the kernel. 4.3BSD Reno introduced the IP_HDRINCL socket option (Section 32.8), so the distinction between inetsw[3] and inetsw[6] is no longer relevant.

The raw interface allows a process to send and receive IP packets without an intervening transport protocol. One use of the raw interface is to implement a transport protocol outside the kernel. Once the protocol has stablized, it can be moved into the kernel to improve its performance and availability to other processes. Another use is for diagnostic tools such as traceroute, which uses the raw IP interface to access IP directly. Chapter 32 discusses the raw IP interface. Figure 7.14 summarizes the IP protosw structures.

in_proto.c

```
39 struct protosw inetsw[] =
40 {
41     {0, &inetdomain, 0, 0,
42      0, ip_output, 0, 0,
43      0,
44      ip_init, 0, ip_slowtimo, ip_drain, ip_sysctl
45     },
46     {SOCK_DGRAM, &inetdomain, IPPROTO_UDP, PR_ATOMIC | PR_ADDR,
47      udp_input, 0, udp_ctlinput, ip_ctloutput,
48      udp_usrreq,
49      udp_init, 0, 0, 0, udp_sysctl
50     },
51     {SOCK_STREAM, &inetdomain, IPPROTO_TCP, PR_CONNREQUIRED | PR_WANTRCVD,
52      tcp_input, 0, tcp_ctlinput, tcp_ctloutput,
53      tcp_usrreq,
54      tcp_init, tcp_fasttimo, tcp_slowtimo, tcp_drain,
55     },
56     {SOCK_RAW, &inetdomain, IPPROTO_RAW, PR_ATOMIC | PR_ADDR,
57      rip_input, rip_output, 0, rip_ctloutput,
58      rip_usrreq,
59      0, 0, 0, 0,
60     },
61     {SOCK_RAW, &inetdomain, IPPROTO_ICMP, PR_ATOMIC | PR_ADDR,
62      icmp_input, rip_output, 0, rip_ctloutput,
63      rip_usrreq,
64      0, 0, 0, 0, icmp_sysctl
65     },
66     {SOCK_RAW, &inetdomain, IPPROTO_IGMP, PR_ATOMIC | PR_ADDR,
67      igmp_input, rip_output, 0, rip_ctloutput,
68      rip_usrreq,
69      igmp_init, igmp_fasttimo, 0, 0,
70     },
71     /* raw wildcard */
72     {SOCK_RAW, &inetdomain, 0, PR_ATOMIC | PR_ADDR,
73      rip_input, rip_output, 0, rip_ctloutput,
74      rip_usrreq,
75      rip_init, 0, 0, 0,
76     },
77 };

78 struct domain inetdomain =
79 {AF_INET, "internet", 0, 0, 0,
80  inetsw, &inetsw[sizeof(inetsw) / sizeof(inetsw[0])], 0,
81  rn_inithead, 32, sizeof(struct sockaddr_in)};
```

in_proto.c

Figure 7.13 The Internet `domain` and `protosw` structures.

78–81 The `domain` structure for the Internet protocols is shown at the end of Figure 7.13. The Internet domain uses `AF_INET` style addressing, has a text name of "`internet`", has no initialization or control-message functions, and has its `protosw` structures in the `inetsw` array.

The routing initialization function for the Internet protocols is `rn_inithead`. The

protosw	inetsw[0]	inetsw[3 and 6]	Description
pr_type	*0*	*SOCK_RAW*	IP provides raw packet services
pr_domain	*&inetdomain*	*&inetdomain*	both protocols are part of the Internet domain
pr_protocol	*0*	*IPPROTO_RAW* or *0*	both IPPROTO_RAW (255) and 0 are reserved (RFC 1700) and should never appear in an IP datagram
pr_flags	*0*	*PR_ATOMIC|PR_ADDR*	socket layer flags, not used by IP
pr_input	*null*	*rip_input*	receive unrecognized datagrams from IP, ICMP, or IGMP
pr_output	*ip_output*	*rip_output*	prepare and send datagrams to the IP and hardware layers respectively
pr_ctlinput	*null*	*null*	not used by IP
pr_ctloutput	*null*	*rip_ctloutput*	respond to configuration requests from a process
pr_usrreq	*null*	*rip_usrreq*	respond to protocol requests from a process
pr_init	*ip_init*	*null* or *rip_init*	ip_init does all initialization
pr_fasttimo	*null*	*null*	not used by IP
pr_slowtimo	*ip_slowtimo*	*null*	slow timeout is used by IP reassembly algorithm
pr_drain	*ip_drain*	*null*	release memory if possible
pr_sysctl	*ip_sysctl*	*null*	modify systemwide parameters

Figure 7.14 The IP inetsw entries.

The only difference between inetsw[3] and inetsw[6] is in their pr_protocol numbers and the initialization function rip_init, which is defined only in inetsw[6] so that it is called only once during initialization.

maximum number of significant bits for an IP address is 32, and the size of an Internet routing key is the size of a sockaddr_in structure (16 bytes).

domaininit Function

At system initialization time (Figure 3.23), the kernel calls domaininit to link the domain and protosw structures. domaininit is shown in Figure 7.15.

37–42 The ADDDOMAIN macro declares and links a single domain structure. For example, ADDDOMAIN(unix) expands to

```
extern struct domain unixdomain;
unixdomain.dom_next = domains;
domains = &unixdomain;
```

The __CONCAT macro is defined in sys/defs.h and concatenates two symbols. For example, __CONCAT(unix,domain) produces unixdomain.

43–54 domaininit constructs the list of domains by calling ADDDOMAIN for each supported domain.

uipc_domain.c

```
37 /* simplifies code in domaininit */

38 #define ADDDOMAIN(x)     { \
39     extern struct domain __CONCAT(x,domain); \
40     __CONCAT(x,domain.dom_next) = domains; \
41     domains = &__CONCAT(x,domain); \
42 }

43 domaininit()
44 {
45     struct domain *dp;
46     struct protosw *pr;
47     /* The C compiler usually defines unix. We don't want to get
48      * confused with the unix argument to ADDDOMAIN
49      */

50 #undef unix
51     ADDDOMAIN(unix);
52     ADDDOMAIN(route);
53     ADDDOMAIN(inet);
54     ADDDOMAIN(iso);

55     for (dp = domains; dp; dp = dp->dom_next) {
56         if (dp->dom_init)
57             (*dp->dom_init) ();
58         for (pr = dp->dom_protosw; pr < dp->dom_protoswNPROTOSW; pr++)
59             if (pr->pr_init)
60                 (*pr->pr_init) ();
61     }

62     if (max_linkhdr < 16)       /* XXX */
63         max_linkhdr = 16;
64     max_hdr = max_linkhdr + max_protohdr;
65     max_datalen = MHLEN - max_hdr;
66     timeout(pffasttimo, (void *) 0, 1);
67     timeout(pfslowtimo, (void *) 0, 1);
68 }
```

uipc_domain.c

Figure 7.15 `domaininit` function.

Since the symbol `unix` is often predefined by the C preprocessor, Net/3 explicitly undefines it here so `ADDDOMAIN` works correctly.

Figure 7.16 shows the linked `domain` and `protosw` structures in a kernel configured to support the Internet, Unix, and OSI protocol families.

55–61 The two nested `for` loops locate every domain and protocol in the kernel and call the initialization functions `dom_init` and `pr_init` if they are defined. For the Internet protocols, the following functions are called (Figure 7.13): `ip_init`, `udp_init`, `tcp_init`, `igmp_init`, and `rip_init`.

62–65 The parameters computed in `domaininit` control the layout of packets in the mbufs to avoid extraneous copying of data. `max_linkhdr` and `max_protohdr` are set during protocol initialization. `domaininit` enforces a lower bound of 16 for `max_linkhdr`. The value of 16 leaves room for a 14-byte Ethernet header ending on a 4-byte boundary. Figures 7.17 and 7.18 lists the parameters and typical values.

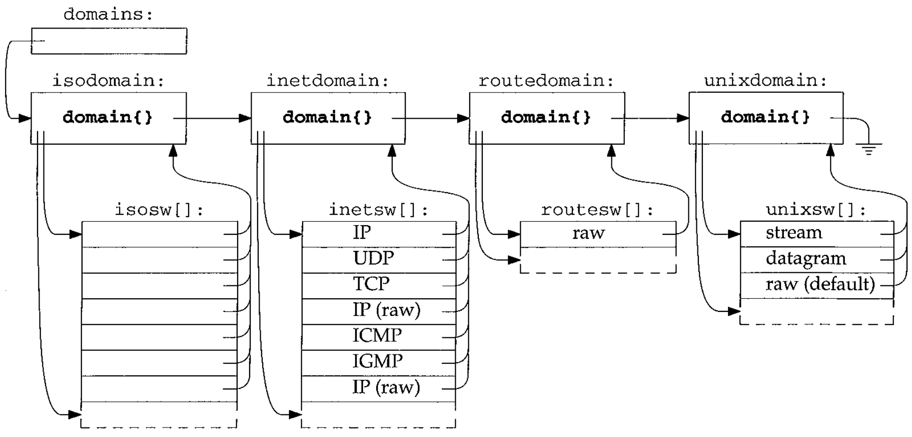


Figure 7.16 The domain list and protosw arrays after initialization.

Variable	Value	Description
max_linkhdr	16	maximum number of bytes added by link layer
max_protohdr	40	maximum number of bytes added by network and transport layers
max_hdr	56	max_linkhdr + max_protohdr
max_datalen	44	number of data bytes available in packet header mbuf after accounting for the link and protocol headers

Figure 7.17 Parameters used to minimize copying of protocol data.

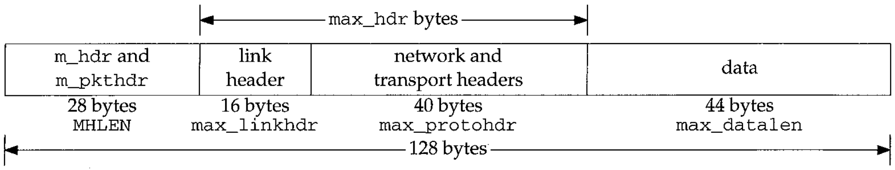


Figure 7.18 Mbuf and associated maximum header lengths.

max_protohdr is a soft limit that measures the expected protocol header size. In the Internet domain, the IP and TCP headers are usually 20 bytes in length but both can be up to 60 bytes. The penalty for exceeding max_protohdr is the time required to push back the data to make room for the larger than expected protocol header.

66–68 domaininit initiates pfslowtimo and pffasttimo by calling timeout. The third argument specifies when the kernel should call the functions, in this case in 1 clock tick. Both functions are shown in Figure 7.19.

uipc_domain.c

```
153 void
154 pfslowtimo(arg)
155 void   *arg;
156 {
157     struct domain *dp;
158     struct protosw *pr;

159     for (dp = domains; dp; dp = dp->dom_next)
160         for (pr = dp->dom_protosw; pr < dp->dom_protoswNPROTOSW; pr++)
161             if (pr->pr_slowtimo)
162                 (*pr->pr_slowtimo) ();
163     timeout(pfslowtimo, (void *) 0, hz / 2);
164 }

165 void
166 pffasttimo(arg)
167 void   *arg;
168 {
169     struct domain *dp;
170     struct protosw *pr;

171     for (dp = domains; dp; dp = dp->dom_next)
172         for (pr = dp->dom_protosw; pr < dp->dom_protoswNPROTOSW; pr++)
173             if (pr->pr_fasttimo)
174                 (*pr->pr_fasttimo) ();
175     timeout(pffasttimo, (void *) 0, hz / 5);
176 }
```

uipc_domain.c

Figure 7.19 `pfslowtimo` and `pffasttimo` functions.

153–176 These nearly identical functions use two `for` loops to call the `pr_slowtimo` or `pr_fasttimo` function for each protocol, if they are defined. The functions schedule themselves to be called 500 and 200 ms later by calling `timeout`, which we described with Figure 3.43.

7.6 `pffindproto` and `pffindtype` Functions

The `pffindproto` and `pffindtype` functions look up a protocol by number (e.g., `IPPROTO_TCP`) or by type (e.g., `SOCK_STREAM`). As we'll see in Chapter 15, these functions are called to locate the appropriate `protosw` entry when a process creates a socket.

69–84 `pffindtype` performs a linear search of `domains` for the specified family and then searches the protocols within the domain for the first one of the specified type.

85–107 `pffindproto` searches `domains` exactly as `pffindtype` does but looks for the family, type, and protocol specified by the caller. If `pffindproto` does not find a (`protocol`, `type`) match within the specified protocol family, and `type` is `SOCK_RAW`, and the domain has a default raw protocol (`pr_protocol` equals 0), then `pffindproto` selects the default raw protocol instead of failing completely. For example, a call such as

uipc_domain.c

```
struct protosw *
pffindtype(family, type)
int     family, type;
{
    struct domain *dp;
    struct protosw *pr;

    for (dp = domains; dp; dp = dp->dom_next)
        if (dp->dom_family == family)
            goto found;
    return (0);
  found:
    for (pr = dp->dom_protosw; pr < dp->dom_protoswNPROTOSW; pr++)
        if (pr->pr_type && pr->pr_type == type)
            return (pr);
    return (0);
}

struct protosw *
pffindproto(family, protocol, type)
int     family, protocol, type;
{
    struct domain *dp;
    struct protosw *pr;
    struct protosw *maybe = 0;

    if (family == 0)
        return (0);
    for (dp = domains; dp; dp = dp->dom_next)
        if (dp->dom_family == family)
            goto found;
    return (0);
  found:
    for (pr = dp->dom_protosw; pr < dp->dom_protoswNPROTOSW; pr++) {
        if ((pr->pr_protocol == protocol) && (pr->pr_type == type))
            return (pr);

        if (type == SOCK_RAW && pr->pr_type == SOCK_RAW &&
            pr->pr_protocol == 0 && maybe == (struct protosw *) 0)
            maybe = pr;
    }
    return (maybe);
}
```

uipc_domain.c

Figure 7.20 pffindproto and pffindtype functions.

```
pffindproto(PF_INET, 27, SOCK_RAW);
```

returns a pointer to inetsw[6], the default raw IP protocol, since Net/3 does not include support for protocol 27. With access to raw IP, a process could implement protocol 27 services on its own using the kernel to manage the sending and receiving of the IP packets.

Protocol 27 is reserved for the Reliable Datagram Protocol (RFC 1151).

Both functions return a pointer to the `protosw` structure for the selected protocol, or a null pointer if they don't find a match.

Example

We'll see in Section 15.6 that when an application calls

```
socket(PF_INET, SOCK_STREAM, 0);      /* TCP socket */
```

`pffindtype` gets called as

```
pffindtype(PF_INET, SOCK_STREAM);
```

Figure 7.12 shows that `pffindtype` will return a pointer to `inetsw[2]`, since TCP is the first `SOCK_STREAM` protocol in the array. Similarly,

```
socket(PF_INET, SOCK_DGRAM, 0);      /* UDP socket */
```

leads to

```
pffindtype(PF_INET, SOCK_DGRAM);
```

which returns a pointer to UDP in `inetsw[1]`.

7.7 `pfctlinput` Function

The `pfctlinput` function issues a control request to every protocol in every domain. It is used when an event that may affect every protocol occurs, such as an interface shutdown or routing table change. ICMP calls `pfctlinput` when an ICMP redirect message arrives (Figure 11.14), since the redirect can affect all the Internet protocols (e.g., UDP and TCP).

uipc_domain.c

```
142 pfctlinput(cmd, sa)
143 int     cmd;
144 struct sockaddr *sa;
145 {
146     struct domain *dp;
147     struct protosw *pr;

148     for (dp = domains; dp; dp = dp->dom_next)
149         for (pr = dp->dom_protosw; pr < dp->dom_protoswNPROTOSW; pr++)
150             if (pr->pr_ctlinput)
151                 (*pr->pr_ctlinput) (cmd, sa, (caddr_t) 0);
152 }
```

uipc_domain.c

Figure 7.21 `pfctlinput` function.

142–152 The two nested `for` loops locate every protocol in every domain. `pfctlinput` issues the protocol control command specified by `cmd` by calling each protocol's `pr_ctlinput` function. For UDP, `udp_ctlinput` is called and for TCP, `tcp_ctlinput` is called.

7.8 IP Initialization

As shown in Figure 7.13, the Internet domain does not have an initialization function but the individual Internet protocols do. For now, we look only at `ip_init`, the IP initialization function. In Chapters 23 and 24 we discuss the UDP and TCP initialization functions. Before we can discuss the code, we need to describe the `ip_protox` array.

Internet Transport Demultiplexing

A network-level protocol like IP must demultiplex incoming datagrams and deliver them to the appropriate transport-level protocols. To do this, the appropriate `protosw` structure must be derived from a protocol number present in the datagram. For the Internet protocols, this is done by the `ip_protox` array.

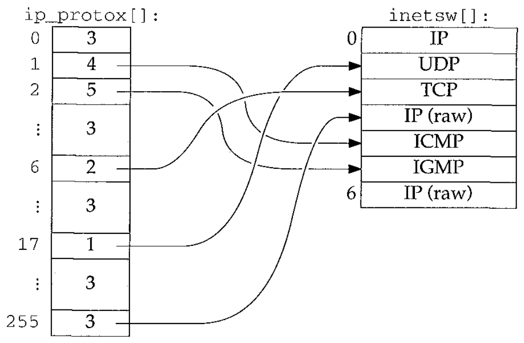


Figure 7.22 The `ip_protox` array maps the protocol number to an entry in the `inetsw` array.

The index into the `ip_protox` array is the protocol value from the IP header (`ip_p`, Figure 8.8). The entry selected is the index of the protocol in the `inetsw` array that processes the datagram. For example, a datagram with a protocol number of 6 is processed by `inetsw[2]`, the TCP protocol. The kernel constructs `ip_protox` during protocol initialization, described in Figure 7.23.

`ip_init` Function

The `ip_init` function is called by `domaininit` (Figure 7.15) at system initialization time.

71–78 `pffindproto` returns a pointer to the raw protocol (`inetsw[3]`, Figure 7.14). Net/3 panics if the raw protocol cannot be located, since it is a required part of the kernel. If it is missing, the kernel has been misconfigured. IP delivers packets that arrive for an unknown transport protocol to this protocol where they may be handled by a process outside the kernel.

79–85 The next two loops initialize the `ip_protox` array. The first loop sets each entry in the array to `pr`, the index of the default protocol (3 from Figure 7.22). The second loop examines each protocol in `inetsw` (other than the entries with protocol numbers of 0 or

ip_input.c

```
71 void
72 ip_init()
73 {
74     struct protosw *pr;
75     int     i;

76     pr = pffindproto(PF_INET, IPPROTO_RAW, SOCK_RAW);
77     if (pr == 0)
78         panic("ip_init");
79     for (i = 0; i < IPPROTO_MAX; i++)
80         ip_protox[i] = pr - inetsw;
81     for (pr = inetdomain.dom_protosw;
82          pr < inetdomain.dom_protoswNPROTOSW; pr++)
83         if (pr->pr_domain->dom_family == PF_INET &&
84             pr->pr_protocol && pr->pr_protocol != IPPROTO_RAW)
85             ip_protox[pr->pr_protocol] = pr - inetsw;
86     ipq.next = ipq.prev = &ipq;
87     ip_id = time.tv_sec & 0xffff;
88     ipintrq.ifq_maxlen = ipqmaxlen;
89     i = (if_index + 1) * (if_index + 1) * sizeof(u_long);
90     ip_ifmatrix = (u_long *) malloc(i, M_RTABLE, M_WAITOK);
91     bzero((char *) ip_ifmatrix, i);
92 }
```

ip_input.c

Figure 7.23 ip_init function.

IPPROTO_RAW) and sets the matching entry in ip_protox to refer to the appropriate inetsw entry. Therefore, pr_protocol in each protosw structure must be the protocol number expected to appear in the incoming datagram.

86–92 ip_init initializes the IP reassembly queue, ipq (Section 10.6), seeds ip_id from the system clock, and sets the maximum size of the IP input queue (ipintrq) to 50 (ipqmaxlen). ip_id is set from the system clock to provide a random starting point for datagram identifiers (Section 10.6). Finally, ip_init allocates a two-dimensional array, ip_ifmatrix, to count packets routed between the interfaces in the system.

There are many variables within Net/3 that may be modified by a system administrator. To allow these variables to be changed at run time and without recompiling the kernel, the default value represented by a constant (IFQ_MAXLEN in this case) is assigned to a variable (ipqmaxlen) at compile time. A system administrator can use a kernel debugger such as adb to change ipqmaxlen and reboot the kernel with the new value. If Figure 7.23 used IFQ_MAXLEN directly, it would require a recompile of the kernel to change the limit.

7.9 sysctl System Call

The sysctl system call accesses and modifies Net/3 systemwide parameters. The system administrator can modify the parameters through the sysctl(8) program. Each parameter is identified by a hierarchical list of integers and has an associated type. The prototype for the system call is:

```
int sysctl(int *name, u_int namelen, void *old, size_t *oldlenp, void *new,
           size_t newlen);
```

name points to an array containing *namelen* integers. The old value is returned in the area pointed to by *oldp*, and the new value is passed in the area pointed to by *newp*.

Figure 7.24 summarizes the organization of the names related to networking.

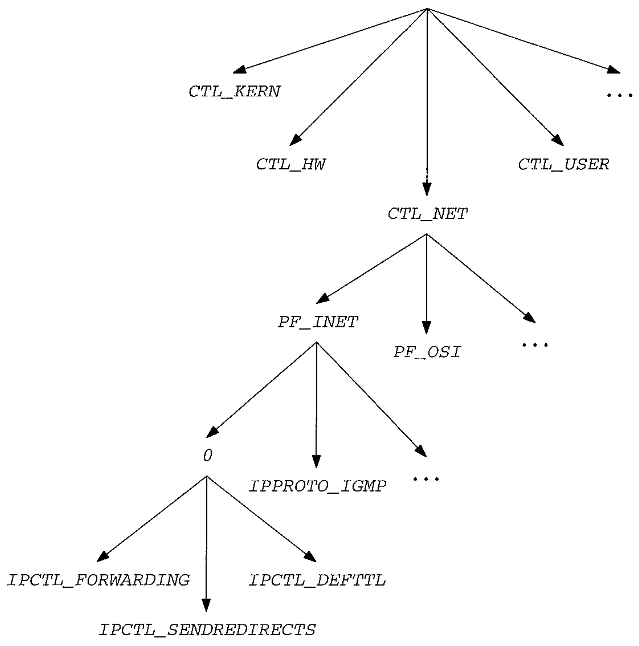


Figure 7.24 sysctl names.

In Figure 7.24, the full name for the IP forwarding flag would be

```
CTL_NET, PF_INET, 0, IPCTL_FORWARDING
```

with the four integers stored in an array.

net_sysctl Function

Each level of the sysctl naming scheme is handled by a different function. Figure 7.25 shows the functions that handle the Internet parameters.

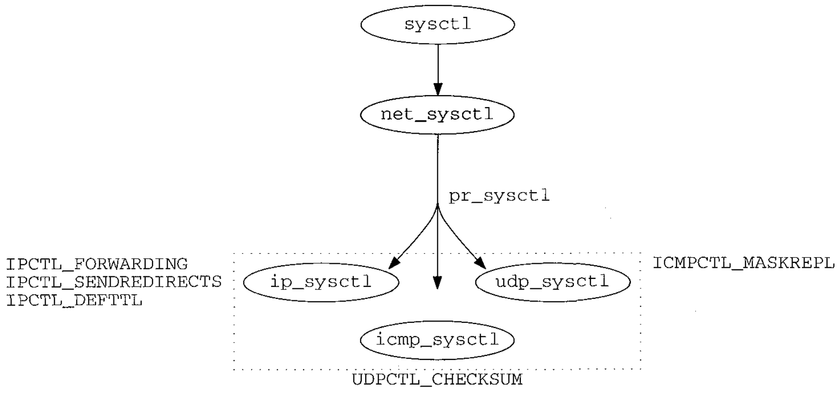


Figure 7.25 sysctl functions for Internet parameters.

The top-level names are processed by sysctl. The network-level names are processed by net_sysctl, which dispatches control based on the family and protocol to the pr_sysctl function specified in the protocol's protosw entry.

> sysctl is implemented in the kernel by the __sysctl function, which we do not discuss in this text. It contains code to move the sysctl arguments to and from the kernel and a switch statement to select the appropriate function to process the arguments, in this case net_sysctl.

Figure 7.26 shows the net_sysctl function.

108–119 The arguments to net_sysctl are the same as those to the sysctl system call with the addition of p, which points to the current process structure.

120–134 The next two integers in the name are taken to be the protocol family and protocol numbers as specified in the domain and protosw structures. If no family is specified, 0 is returned. If a family is specified, the for loop searches the domain list for a matching family. ENOPROTOOPT is returned if a match is not found.

135–141 Within a matching domain, the second for loop locates the first matching protocol that has the pr_sysctl function defined. When a match is found, the request is passed to the pr_sysctl function for the protocol. Notice that name is advanced to pass the remaining integers down to the next level. If no matching protocol is found, ENOPROTOOPT is returned.

Figure 7.27 shows the pr_sysctl functions defined for the Internet protocols.

uipc_domain.c

```
net_sysctl(name, namelen, oldp, oldlenp, newp, newlen, p)
int     *name;
u_int    namelen;
void    *oldp;
size_t *oldlenp;
void    *newp;
size_t  newlen;
struct proc *p;
{
    struct domain *dp;
    struct protosw *pr;
    int     family, protocol;

    /*
     * All sysctl names at this level are nonterminal;
     * next two components are protocol family and protocol number,
     * then at least one additional component.
     */
    if (namelen < 3)
        return (EISDIR);        /* overloaded */
    family = name[0];
    protocol = name[1];

    if (family == 0)
        return (0);
    for (dp = domains; dp; dp = dp->dom_next)
        if (dp->dom_family == family)
            goto found;
    return (ENOPROTOOPT);
  found:
    for (pr = dp->dom_protosw; pr < dp->dom_protoswNPROTOSW; pr++)
        if (pr->pr_protocol == protocol && pr->pr_sysctl)
            return ((*pr->pr_sysctl) (name + 2, namelen - 2,
                                      oldp, oldlenp, newp, newlen));
    return (ENOPROTOOPT);
}
```

uipc_domain.c

Figure 7.26 net_sysctl function.

pr_protocol	inetsw[]	pr_sysctl	Description	Reference
0	0	*ip_sysctl*	IP	Section 8.9
IPPROTO_UDP	1	*udp_sysctl*	UDP	Section 23.11
IPPROTO_ICMP	4	*icmp_sysctl*	ICMP	Section 11.14

Figure 7.27 pr_sysctl functions for the Internet protocol family.

In the routing domain, pr_sysctl points to the sysctl_rtable function, which is described in Chapter 19.

7.10 Summary

We started this chapter by describing the domain and protosw structures that describe and group protocols within the Net/3 kernel. We saw that all the protosw structures for a domain are allocated in an array at compile time and that inetdomain and the inetsw array describe the Internet protocols. We took a closer look at the three inetsw entries that describe the IP protocol: one for the kernel's use and the other two for access to IP by a process.

At system initialization time domaininit links the domains into the domains list, calls the domain and protocol initialization functions, and calls the fast and slow timeout functions.

The two functions pffindproto and pffindtype search the domain and protocol lists by protocol number or type. pfctlinput sends a control command to every protocol.

Finally we described the IP initialization procedure including transport demultiplexing by the ip_protox array.

Exercises

7.1 What call to the pffindproto returns a pointer to inetsw[6]?

8

IP: Internet Protocol

8.1 Introduction

In this chapter we describe the structure of an IP packet and the basic IP processing including input, forwarding, and output. We assume that the reader is familiar with the basic operation of the IP protocol. For more background on IP, see Chapters 3, 9 and 12 of Volume 1. RFC 791 [Postel 1981a] is the official specification for IP. RFC 1122 [Braden 1989a] contains clarifications of RFC 791.

In Chapter 9 we discuss option processing and in Chapter 10 we discuss fragmentation and reassembly. Figure 8.1 illustrates the general organization of the IP layer.

We saw in Chapter 4 how network interfaces place incoming IP packets on the IP input queue, `ipintrq`, and how they schedule a software interrupt. Since hardware interrupts have a higher priority than software interrupts, several packets may be placed on the queue before a software interrupt occurs. During software interrupt processing, the `ipintr` function removes and processes packets from `ipintrq` until the queue is empty. At the final destination, IP reassembles packets into datagrams and passes the datagrams directly to the appropriate transport-level protocol by a function call. If the packets haven't reached their final destination, IP passes them to `ip_forward` if the host is configured to act as a router. The transport protocols and `ip_forward` pass outgoing packets to `ip_output`, which completes the IP header, selects an output interface, and fragments the outgoing packet if necessary. The resulting packets are passed to the appropriate network interface output function.

When an error occurs, IP discards the packet and under certain conditions may send an error message to the source of the original packet. These messages are part of ICMP (Chapter 11). Net/3 sends ICMP error messages by calling `icmp_error`, which accepts an mbuf containing the erroneous packet, the type of error found, and an option

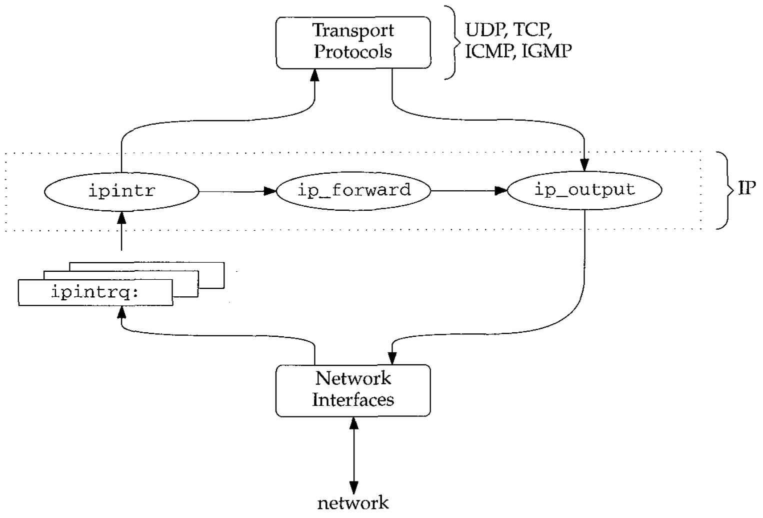


Figure 8.1 IP layer processing.

code that provides additional information depending on the type of error. In this chapter, we describe why and when IP sends ICMP messages, but we postpone a detailed discussion of ICMP itself until Chapter 11.

8.2 Code Introduction

Two headers and three C files are discussed in this chapter.

File	Description
`net/route.h`	route entries
`netinet/ip.h`	IP header structure
`netinet/ip_input.c`	IP input processing
`netinet/ip_output.c`	IP output processing
`netinet/in_cksum.c`	Internet checksum algorithm

Figure 8.2 Files discussed in this chapter.

Global Variables

Several global variables appear in the IP processing code. They are described in Figure 8.3.

Variable	Datatype	Description
`in_ifaddr`	`struct in_ifaddr *`	IP address list
`ip_defttl`	`int`	default TTL for IP packets
`ip_id`	`int`	last ID assigned to an outgoing IP packet
`ip_protox`	`int[]`	demultiplexing array for IP packets
`ipforwarding`	`int`	should the system forward IP packets?
`ipforward_rt`	`struct route`	cache of most recent forwarded route
`ipintrq`	`struct ifqueue`	IP input queue
`ipqmaxlen`	`int`	maximum length of IP input queue
`ipsendredirects`	`int`	should the system send ICMP redirects?
`ipstat`	`struct ipstat`	IP statistics

Figure 8.3 Global variables introduced in this chapter.

Statistics

All the statistics collected by IP are found in the `ipstat` structure described by Figure 8.4. Figure 8.4 shows some sample output of these statistics, from the `netstat -s` command. These statistics were collected after the host had been up for 30 days.

`ipstat` member	Description	Used by SNMP
`ips_badhlen`	#packets with invalid IP header length	•
`ips_badlen`	#packets with inconsistent IP header and IP data lengths	•
`ips_badoptions`	#packets discovered with errors in option processing	•
`ips_badsum`	#packets with bad checksum	•
`ips_badvers`	#packets with an IP version other than 4	•
`ips_cantforward`	#packets received for unreachable destination	•
`ips_delivered`	#datagrams delivered to upper level	•
`ips_forward`	#packets forwarded	•
`ips_fragdropped`	#fragments dropped (duplicates or out of space)	•
`ips_fragments`	#fragments received	•
`ips_fragtimeout`	#fragments timed out	•
`ips_noproto`	#packets with an unknown or unsupported protocol	•
`ips_reassembled`	#datagrams reassembled	•
`ips_tooshort`	#packets with invalid data length	•
`ips_toosmall`	#packets too small to contain IP packet	•
`ips_total`	total #packets received	•
`ips_cantfrag`	#packets discarded because of the don't fragment bit	•
`ips_fragmented`	#datagrams successfully fragmented	•
`ips_localout`	#datagrams generated at system (i.e., not forwarded)	•
`ips_noroute`	#packets discarded—no route to destination	•
`ips_odropped`	#packets dropped because of resource shortages	•
`ips_ofragments`	#fragments created for output	•
`ips_rawout`	total #raw ip packets generated	
`ips_redirectsent`	#redirect messages sent	

Figure 8.4 Statistics collected in this chapter.

netstat -s output	ipstat members
27,881,978 total packets received	ips_total
6 bad header checksums	ips_badsum
9 with size smaller than minimum	ips_tooshort
14 with data size < data length	ips_toosmall
0 with header length < data size	ips_badhlen
0 with data length < header length	ips_badlen
0 with bad options	ips_badoptions
0 with incorrect version number	ips_badvers
72,786 fragments received	ips_fragments
0 fragments dropped (dup or out of space)	ips_fragdropped
349 fragments dropped after timeout	ips_fragtimeout
16,557 packets reassembled ok	ips_reassembled
27,390,665 packets for this host	ips_delivered
330,882 packets for unknown/unsupported protocol	ips_noproto
97,939 packets forwarded	ips_forward
6,228 packets not forwardable	ips_cantforward
0 redirects sent	ips_redirectsent
29,447,726 packets sent from this host	ips_localout
769 packets sent with fabricated ip header	ips_rawout
0 output packets dropped due to no bufs, etc.	ips_odropped
0 output packets discarded due to no route	ips_noroute
260,484 output datagrams fragmented	ips_fragmented
796,084 fragments created	ips_ofragments
0 datagrams that can't be fragmented	ips_cantfrag

Figure 8.5 Sample IP statistics.

The value for ips_noproto is high because it can count ICMP host unreachable messages when there is no process ready to receive the messages. See Section 32.5 for more details.

SNMP Variables

Figure 8.6 shows the relationship between the SNMP variables in the IP group and the statistics collected by Net/3.

SNMP variable	ipstat member	Description
ipDefaultTTL	ip_defttl	default TTL for datagrams (64 "hops")
ipForwarding	ipforwarding	is system acting as a router?
ipReasmTimeout	IPFRAGTTL	reassembly timeout for fragments (30 seconds)
ipInReceives	ips_total	total #IP packets received
ipInHdrErrors	ips_badsum + ips_tooshort + ips_toosmall + ips_badhlen + ips_badlen + ips_badoptions + ips_badvers	#packets with errors in IP header
ipInAddrErrors	ips_cantforward	#IP packets discarded because of misdelivery (ip_output failure also)
ipForwDatagrams	ips_forward	#IP packets forwarded
ipReasmReqds	ips_fragments	#fragments received
ipReasmFails	ips_fragdropped + ips_fragtimeout	#fragments dropped
ipReasmOKs	ips_reassembled	#datagrams successfully reassembled
ipInDiscards	(not implemented)	#datagrams discarded because of resource limitations
ipInUnknownProtos	ips_noproto	#datagrams with an unknown or unsupported protocol
ipInDelivers	ips_delivered	#datagrams delivered to transport layer
ipOutRequests	ips_localout	#datagrams generated by transport layers
ipFragOKs	ips_fragmented	#datagrams successfully fragmented
ipFragFails	ips_cantfrag	#IP packets discarded because of don't fragment bit
ipFragCreates	ips_ofragments	#fragments created for output
ipOutDiscards	ips_odropped	#IP packets dropped because of resource shortages
ipOutNoRoutes	ips_noroute	#IP packets discarded because of no route

Figure 8.6 Simple SNMP variables in IP group.

8.3 IP Packets

To be accurate while discussing Internet protocol processing, we must define a few terms. Figure 8.7 illustrates the terms that describe data as it passes through the various Internet layers.

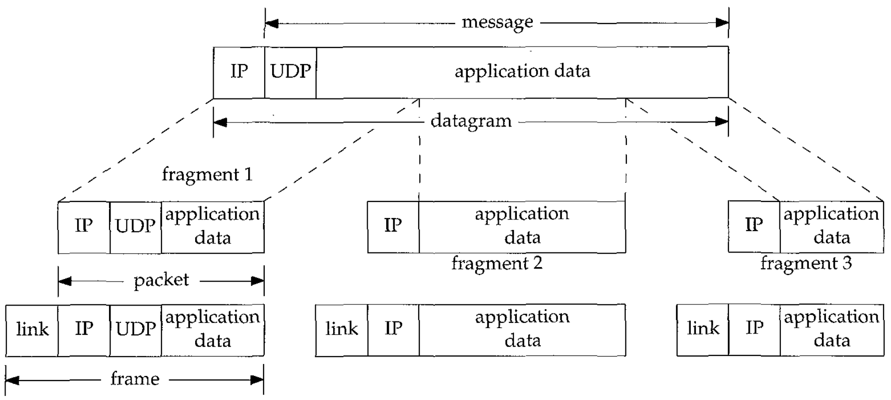


Figure 8.7 Frames, packets, fragments, datagrams, and messages.

We call the data passed to IP by a transport protocol a *message*. A message typically contains a transport header and application data. UDP is the transport protocol illustrated in Figure 8.7. IP prepends its own header to the message to form a *datagram*. If the datagram is too large for transmission on the selected network, IP splits the datagram into several *fragments*, each of which contains its own IP header and a portion of the original datagram. Figure 8.7 shows a datagram split into three fragments.

An IP fragment or an IP datagram small enough to not require fragmentation are called *packets* when presented to the data-link layer for transmission. The data-link layer prepends its own header and transmits the resulting *frame*.

IP concerns itself only with the IP header and does not examine or modify the message itself (other than to perform fragmentation). Figure 8.8 shows the structure of the IP header.

Figure 8.8 includes the member names of the ip structure (shown in Figure 8.9) through which Net/3 accesses the IP header.

47–67 Since the physical order of bit fields in memory is machine and compiler dependent, the #ifs ensure that the compiler lays out the structure members in the order specified by the IP standard. In this way, when Net/3 overlays an ip structure on an IP packet in memory, the structure members access the correct bits in the packet.

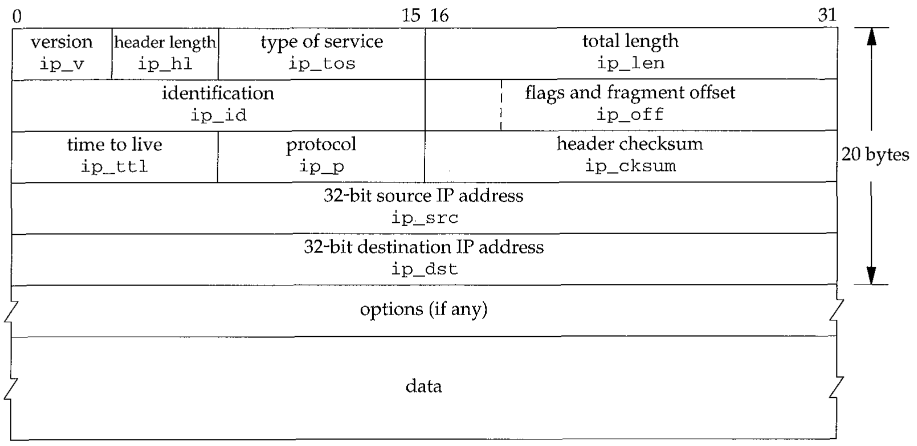


Figure 8.8 IP datagram, including the ip structure names.

ip.h

```
/*
 * Structure of an internet header, naked of options.
 *
 * We declare ip_len and ip_off to be short, rather than u_short
 * pragmatically since otherwise unsigned comparisons can result
 * against negative integers quite easily, and fail in subtle ways.
 */
struct ip {
#if BYTE_ORDER == LITTLE_ENDIAN
    u_char  ip_hl:4,            /* header length */
            ip_v:4;             /* version */
#endif
#if BYTE_ORDER == BIG_ENDIAN
    u_char  ip_v:4,             /* version */
            ip_hl:4;            /* header length */
#endif
    u_char  ip_tos;             /* type of service */
    short   ip_len;             /* total length */
    u_short ip_id;              /* identification */
    short   ip_off;             /* fragment offset field */
#define IP_DF 0x4000            /* dont fragment flag */
#define IP_MF 0x2000            /* more fragments flag */
#define IP_OFFMASK 0x1fff       /* mask for fragmenting bits */
    u_char  ip_ttl;             /* time to live */
    u_char  ip_p;               /* protocol */
    u_short ip_sum;             /* checksum */
    struct in_addr ip_src, ip_dst;  /* source and dest address */
};
```

ip.h

Figure 8.9 ip structure.

The IP header contains the format of the IP packet and its contents along with addressing, routing, and fragmentation information.

The format of an IP packet is specified by `ip_v`, the version, which is always 4; `ip_hl`, the header length measured in 4-byte units; `ip_len`, the packet length measured in bytes; `ip_p`, the transport protocol that created the data within the packet; and `ip_sum`, the checksum that detects changes to the header while in transit.

A standard IP header is 20 bytes long, so `ip_hl` must be greater than or equal to 5. A value greater than 5 indicates that IP options appear just after the standard header. The maximum value of `ip_hl` is 15 ($2^4 - 1$), which allows for up to 40 bytes of options ($20 + 40 = 60$). The maximum length of an IP datagram is 65535 ($2^{16} - 1$) bytes since `ip_len` is a 16-bit field. Figure 8.10 illustrates this organization.

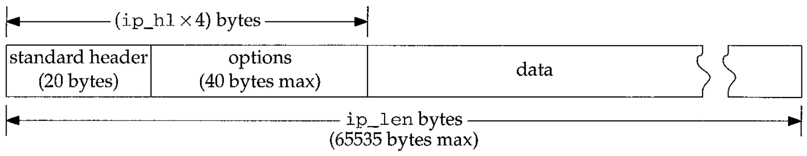


Figure 8.10 Organization of an IP packet with options.

Because `ip_hl` is measured in 4-byte units, IP options must always be padded to a 4-byte boundary.

8.4 Input Processing: `ipintr` Function

In Chapters 3, 4, and 5 we described how our example network interfaces queue incoming datagrams for protocol processing:

1. The Ethernet interface demultiplexes incoming frames with the type field found in the Ethernet header (Section 4.3).
2. The SLIP interface handles only IP packets, so demultiplexing is unnecessary (Section 5.3).
3. The loopback interface combines output and input processing in the function `looutput` and demultiplexes datagrams with the `sa_family` member of the destination address (Section 5.4).

In each case, after the interface queues the packet on `ipintrq`, it schedules a software interrupt through `schednetisr`. When the software interrupt occurs, the kernel calls `ipintr` if IP processing has been scheduled by `schednetisr`. Before the call to `ipintr`, the CPU priority is changed to `splnet`.

`ipintr` Overview

`ipintr` is a large function that we discuss in four parts: (1) verification of incoming packets, (2) option processing and forwarding, (3) packet reassembly, and (4) demultiplexing. Packet reassembly occurs in ipintr, but it is complex enough that we discuss it separately in Chapter 10. Figure 8.11 shows the overall organization of ipintr.

ip_input.c

```
100 void
101 ipintr()
102 {
103     struct ip *ip;
104     struct mbuf *m;
105     struct ipq *fp;
106     struct in_ifaddr *ia;
107     int     hlen, s;

108   next:
109     /*
110      * Get next datagram off input queue and get IP header
111      * in first mbuf.
112      */
113     s = splimp();
114     IF_DEQUEUE(&ipintrq, m);
115     splx(s);
116     if (m == 0)
117         return;

                        /* input packet processing */
                 /* Figures 8.12, 8.13, 8.15, 10.11, and 12.40 */

332     goto next;
333   bad:
334     m_freem(m);
335     goto next;
336 }
```

ip_input.c

Figure 8.11 ipintr function.

100–117 The label next marks the start of the main packet processing loop. ipintr removes packets from ipintrq and processes them until the queue is empty. If control falls through to the end of the function, the goto passes control back to the top of the function at next. ipintr blocks incoming packets with splimp so that the network interrupt routines (such as slinput and ether_input) don't run while it accesses the queue.

332–336 The label bad marks the code that silently discards packets by freeing the associated mbuf and returning to the top of the processing loop at next. Throughout ipintr, errors are handled by jumping to bad.

Verification

We start with Figure 8.12: dequeueing packets from ipintrq and verifying their contents. Damaged or erroneous packets are silently discarded.

ip_input.c

```
    /*
     * If no IP addresses have been set yet but the interfaces
     * are receiving, can't do anything with incoming packets yet.
     */
    if (in_ifaddr == NULL)
        goto bad;
    ipstat.ips_total++;
    if (m->m_len < sizeof(struct ip) &&
            (m = m_pullup(m, sizeof(struct ip))) == 0) {
        ipstat.ips_toosmall++;
        goto next;
    }
    ip = mtod(m, struct ip *);
    if (ip->ip_v != IPVERSION) {
        ipstat.ips_badvers++;
        goto bad;
    }
    hlen = ip->ip_hl << 2;
    if (hlen < sizeof(struct ip)) {     /* minimum header length */
        ipstat.ips_badhlen++;
        goto bad;
    }
    if (hlen > m->m_len) {
        if ((m = m_pullup(m, hlen)) == 0) {
            ipstat.ips_badhlen++;
            goto next;
        }
        ip = mtod(m, struct ip *);
    }
    if (ip->ip_sum = in_cksum(m, hlen)) {
        ipstat.ips_badsum++;
        goto bad;
    }
    /*
     * Convert fields to host representation.
     */
    NTOHS(ip->ip_len);
    if (ip->ip_len < hlen) {
        ipstat.ips_badlen++;
        goto bad;
    }
    NTOHS(ip->ip_id);
    NTOHS(ip->ip_off);

    /*
     * Check that the amount of data in the buffers
     * is as at least much as the IP header would have us expect.
     * Trim mbufs if longer than we expect.
     * Drop packet if shorter than we expect.
     */
    if (m->m_pkthdr.len < ip->ip_len) {
        ipstat.ips_tooshort++;
        goto bad;
    }
    if (m->m_pkthdr.len > ip->ip_len) {
        if (m->m_len == m->m_pkthdr.len) {
            m->m_len = ip->ip_len;
            m->m_pkthdr.len = ip->ip_len;
        } else
            m_adj(m, ip->ip_len - m->m_pkthdr.len);
    }
```
ip_input.c

Figure 8.12 ipintr function.

IP version

118–134 If the in_ifaddr list (Section 6.5) is empty, no IP addresses have been assigned to the network interfaces, and ipintr must discard all IP packets; without addresses, ipintr can't determine whether the packet is addressed to the system. Normally this is a transient condition occurring during system initialization when the interfaces are operating but have not yet been configured. We described address assignment in Section 6.6.

Before ipintr accesses any IP header fields, it must verify that ip_v is 4 (IPVERSION). RFC 1122 requires an implementation to silently discard packets with unrecognized version numbers.

Net/2 didn't check ip_v. Most IP implementations in use today, including Net/2, were created after IP version 4 was standardized and have never needed to distinguish between packets from different IP versions. Since revisions to IP are now in progress, implementations in the near future will have to check ip_v.

IEN 119 [Forgie 1979] and RFC 1190 [Topolcic 1990] describe experimental protocols using IP versions 5 and 6. Version 6 has also been selected as the version for the next revision to the official IP standard (IPv6). Versions 0 and 15 are reserved, and the remaining versions are unassigned.

In C, the easiest way to process data located in an untyped area of memory is to overlay a structure on the area of memory and process the structure members instead of the raw bytes. As described in Chapter 2, an mbuf chain stores a logical sequence of bytes, such as an IP packet, into many physical mbufs connected to each other on a linked list. Before the overlay technique can be applied to the IP packet headers, the header must reside in a contiguous area of memory (i.e., it isn't split between two mbufs).

135–146 The following steps ensure that the IP header (including options) is in a contiguous area of memory:

- If the data within the first mbuf is smaller than a standard IP header (20 bytes), m_pullup relocates the standard header into a contiguous area of memory.

  It is improbable that the link layer would split even the largest (60 bytes) IP header into two mbufs necessitating the use of m_pullup as described.

- ip_hl is multiplied by 4 to get the header length in bytes, which is saved in hlen.

- If `hlen`, the length of the IP packet header in bytes, is less than the length of a standard header (20 bytes), it is invalid and the packet is discarded.
- If the entire header is still not in the first mbuf (i.e., the packet contains IP options), `m_pullup` finishes the job.

Again, this should not be necessary.

Checksum processing is an important part of all the Internet protocols. Each protocol uses the same algorithm (implemented by the function `in_cksum`) but on different parts of the packet. For IP, the checksum protects only the IP header (and options if present). For transport protocols, such as UDP or TCP, the checksum covers the data portion of the packet and the transport header.

IP checksum

147–150 `ipintr` stores the checksum computed by `in_cksum` in the `ip_sum` field of the header. An undamaged header should have a checksum of 0.

As we'll see in Section 8.7, `ip_sum` must be cleared before the checksum on an outgoing packet is computed. By storing the result from `in_cksum` in `ip_sum`, the packet is prepared for forwarding (although the TTL has not been decremented yet). The `ip_output` function does not depend on this behavior; it recomputes the checksum for the forwarded packet.

If the result is nonzero the packet is silently discarded. We discuss `in_cksum` in more detail in Section 8.7.

Byte ordering

151–160 The Internet standards are careful to specify the byte ordering of multibyte integer values in protocol headers. `NTOHS` converts all the 16-bit values in the IP header from from network byte order to host byte order: the packet length (`ip_len`), the datagram identifier (`ip_id`), and the fragment offset (`ip_off`). `NTOHS` is a null macro if the two formats are the same. Conversion to host byte order here obviates the need to perform a conversion every time Net/3 examines the fields.

Packet length

161–177 If the logical size of the packet (`ip_len`) is greater than the amount of data stored in the mbuf (`m_pkthdr.len`), some bytes are missing and the packet is dropped. If the mbuf is larger than the packet, the extra bytes are trimmed.

A common cause for lost bytes is data arriving on a serial device with little or no buffering, such as on many personal computers. The incoming bytes are discarded by the device and IP discards the resulting packet.

These extra bytes may arise, for example, on an Ethernet device when an IP packet is smaller than the minimum size required by Ethernet. The frame is transmitted with extra bytes that are discarded here. This is one reason why the length of the IP packet is stored in the header; IP allows the link layer to pad packets.

At this point, the complete IP header is available, the logical size and the physical size of the packet are the same, and the checksum indicates that the header arrived undamaged.

To Forward or Not To Forward?

The next section of ipintr, shown in Figure 8.13, calls ip_dooptions (Chapter 9) to process IP options and then determines whether or not the packet has reached its final destination. If it hasn't reached its final destination, Net/3 may attempt to forward the packet (if the system is configured as a router). If it has reached its final destination, it is passed to the appropriate transport-level protocol.

ip_input.c

```
    /*
     * Process options and, if not destined for us,
     * ship it on.  ip_dooptions returns 1 when an
     * error was detected (causing an icmp message
     * to be sent and the original packet to be freed).
     */
    ip_nhops = 0;               /* for source routed packets */
    if (hlen > sizeof(struct ip) && ip_dooptions(m))
            goto next;

    /*
     * Check our list of addresses, to see if the packet is for us.
     */
    for (ia = in_ifaddr; ia; ia = ia->ia_next) {
#define satosin(sa) ((struct sockaddr_in *)(sa))

        if (IA_SIN(ia)->sin_addr.s_addr == ip->ip_dst.s_addr)
            goto ours;

        /* Only examine broadcast addresses for the receiving interface */
        if (ia->ia_ifp == m->m_pkthdr.rcvif &&
            (ia->ia_ifp->if_flags & IFF_BROADCAST)) {
            u_long  t;

            if (satosin(&ia->ia_broadaddr)->sin_addr.s_addr ==
                ip->ip_dst.s_addr)
                goto ours;
            if (ip->ip_dst.s_addr == ia->ia_netbroadcast.s_addr)
                goto ours;
            /*
             * Look for all-0's host part (old broadcast addr),
             * either for subnet or net.
             */
            t = ntohl(ip->ip_dst.s_addr);
            if (t == ia->ia_subnet)
                goto ours;
            if (t == ia->ia_net)
                goto ours;
        }
    }

                      /* multicast code (Figure 12.39) */
```

```
258     if (ip->ip_dst.s_addr == (u_long) INADDR_BROADCAST)
259         goto ours;
260     if (ip->ip_dst.s_addr == INADDR_ANY)
261         goto ours;

262     /*
263      * Not for us; forward if possible and desirable.
264      */
265     if (ipforwarding == 0) {
266         ipstat.ips_cantforward++;
267         m_freem(m);
268     } else
269         ip_forward(m, 0);
270     goto next;

271   ours:
```
ip_input.c

Figure 8.13 ipintr continued.

Option processing

178–186 The source route from the previous packet is discarded by clearing ip_nhops (Section 9.6). If the packet header is larger than a default header, it must include options that are processed by ip_dooptions. If ip_dooptions returns 0, ipintr should continue processing the packet; otherwise ip_dooptions has completed processing of the packet by forwarding or discarding it, and ipintr can process the next packet on the input queue. We postpone further discussion of option processing until Chapter 9.

After option processing, ipintr decides whether the packet has reached its final destination by comparing ip_dst in the IP header with the IP addresses configured for all the local interfaces. ipintr must consider several broadcast addresses, one or more unicast addresses, and any multicast addresses that are associated with the interface.

Final destination?

187–261 ipintr starts by traversing in_ifaddr (Figure 6.5), the list of configured Internet addresses, to see if there is a match with the destination address of the packet. A series of comparisons are made for each in_ifaddr structure found in the list. There are four general cases to consider:

- an exact match with one of the interface addresses (first row of Figure 8.14),
- a match with the one of the broadcast addresses associated with the *receiving* interface (middle four rows of Figure 8.14),
- a match with one of the multicast groups associated with the *receiving* interface (Figure 12.39), or
- a match with one of the two limited broadcast addresses (last row of Figure 8.14).

Figure 8.14 illustrates the addresses that would be tested for a packet arriving on the Ethernet interface of the host sun in our sample network, excluding multicast addresses, which we discuss in Chapter 12.

Variable	Ethernet	SLIP	Loopback	Lines (Figure 8.13)
`ia_addr`	140.252.13.33	140.252.1.29	127.0.0.1	192–193
`ia_broadaddr`	140.252.13.224			198–200
`ia_netbroadcast`	140.252.255.255			201–202
`ia_subnet`	140.252.13.32			207–209
`ia_net`	140.252.0.0			210–211
`INADDR_BROADCAST`		255.255.255.255		258–259
`INADDR_ANY`		0.0.0.0		260–261

Figure 8.14 Comparisons to determine whether or not a packet has reached its final destination.

The tests with `ia_subnet`, `ia_net`, and `INADDR_ANY` are not required as they represent obsolete broadcast addresses used by 4.2BSD. Unfortunately, many TCP/IP implementations have been derived from 4.2BSD, so it may be important to recognize these old broadcast addresses on some networks.

Forwarding

262–271 If `ip_dst` does not match any of the addresses, the packet has not reached its final destination. If `ipforwarding` is not set, the packet is discarded. Otherwise, `ip_forward` attempts to route the packet toward its final destination.

A host may discard packets that arrive on an interface other than the one specified by the destination address of the packet. In this case, Net/3 would not search the entire `in_ifaddr` list; only addresses assigned to the receiving interface would be considered. RFC 1122 calls this a *strong end system* model.

For a multihomed host, it is uncommon for a packet to arrive at an interface that does not correspond to the packet's destination address, unless specific host routes have been configured. The host routes force neighboring routers to consider the multihomed host as the next-hop router for the packets. The *weak end system* model requires that the host accept these packets. An implementor is free to choose either model. Net/3 implements the weak end system model.

Reassembly and Demultiplexing

Finally, we look at the last section of `ipintr` (Figure 8.15) where reassembly and demultiplexing occur. We have omitted the reassembly code and postpone its discussion until Chapter 10. The omitted code sets the pointer `ip` to null if it could not reassemble a complete datagram. Otherwise, ip points to a complete datagram that has reached its final destination.

ip_input.c

```
                    /* reassembly (Figure 10.11) */

325     /*
326      * If control reaches here, ip points to a complete datagram.
327      * Otherwise, the reassembly code jumps back to next (Figure 8.11)
328      * Switch out to protocol's input routine.
329      */
330     ipstat.ips_delivered++;
331     (*inetsw[ip_protox[ip->ip_p]].pr_input) (m, hlen);
332     goto next;
```

ip_input.c

Figure 8.15 ipintr continued.

Transport demultiplexing

325–332 The protocol specified in the datagram is mapped by ip_p with the ip_protox array (Figure 7.22) to an index into the inetsw array. ipintr calls the pr_input function from the selected protosw structure to process the transport message contained within the datagram. When pr_input returns, ipintr proceeds with the next packet on ipintrq.

It is important to notice that transport-level processing for each packet occurs within the processing loop of ipintr. There is no queueing of incoming packets between IP and the transport protocols, unlike the queueing in SVR4 streams implementations of TCP/IP.

8.5 Forwarding: ip_forward Function

A packet arriving at a system other than its final destination needs to be forwarded. ipintr calls the function ip_forward, which implements the forwarding algorithm, only when ipforwarding is nonzero (Section 6.1) or when the packet includes a source route (Section 9.6). When the packet includes a source route, ip_dooptions calls ip_forward with the second argument, srcrt, set to 1.

ip_forward interfaces with the routing tables through a route structure shown in Figure 8.16

route.h

```
struct route {
    struct rtentry *ro_rt;        /* pointer to struct with information */
    struct sockaddr ro_dst;       /* destination of this route */
};
```

route.h

Figure 8.16 route structure.

46–49 There are only two members in a `route` structure: `ro_rt`, a pointer to an `rtentry` structure; and `ro_dst`, a `sockaddr` structure, which specifies the destination associated with the route entry pointed to by `ro_rt`. The destination is the key used to find route information in the kernel's routing tables. Chapter 18 has a detailed description of the `rtentry` structure and the routing tables.

We show `ip_forward` in two parts. The first part makes sure the system is permitted to forward the packet, updates the IP header, and selects a route for the packet. The second part handles ICMP redirect messages and passes the packet to `ip_output` for transmission.

Is packet eligible for forwarding?

867–871 The first argument to `ip_forward` is a pointer to an mbuf chain containing the packet to be forwarded. If the second argument, `srcrt`, is nonzero, the packet is being forwarded because of a source route option (Section 9.6).

879–884 The `if` statement identifies and discards the following packets:

- link-level broadcasts

  Any network interface driver that supports broadcasts must set the `M_BCAST` flag for a packet received as a broadcast. `ether_input` (Figure 4.13) sets `M_BCAST` if the packet was addressed to the Ethernet broadcast address. Link-level broadcast packets are never forwarded.

  Packets addressed to a unicast IP addresses but sent as a link-level broadcast are prohibited by RFC 1122 and are discarded here.

- loopback packets

  `in_canforward` returns 0 for packets addressed to the loopback network. These packets may have been passed to `ip_forward` by `ipintr` because the loopback interface was not configured correctly.

- network 0 and class E addresses

  `in_canforward` returns 0 for these packets. These destination addresses are invalid and packets addressed to them should not be circulating in the network since no host will accept them.

- class D addresses

  Packets addressed to a class D address should be processed by the multicast forwarding function, `ip_mforward`, not by `ip_forward`. `in_canforward` rejects class D (multicast) addresses.

RFC 791 specifies that every system that processes a packet must decrement the time-to-live (TTL) field by at least 1 even though TTL is measured in seconds. Because of this requirement, TTL is usually considered a bound on the number of hops an IP packet may traverse before being discarded. Technically, a router that held a packet for more than 1 second could decrement `ip_ttl` by more than 1.

ip_input.c

```
void
ip_forward(m, srcrt)
struct mbuf *m;
int     srcrt;
{
    struct ip *ip = mtod(m, struct ip *);
    struct sockaddr_in *sin;
    struct rtentry *rt;
    int     error, type = 0, code;
    struct mbuf *mcopy;
    n_long  dest;
    struct ifnet *destifp;

    dest = 0;
    if (m->m_flags & M_BCAST || in_canforward(ip->ip_dst) == 0) {
        ipstat.ips_cantforward++;
        m_freem(m);
        return;
    }
    HTONS(ip->ip_id);
    if (ip->ip_ttl <= IPTTLDEC) {
        icmp_error(m, ICMP_TIMXCEED, ICMP_TIMXCEED_INTRANS, dest, 0);
        return;
    }
    ip->ip_ttl -= IPTTLDEC;

    sin = (struct sockaddr_in *) &ipforward_rt.ro_dst;
    if ((rt = ipforward_rt.ro_rt) == 0 ||
        ip->ip_dst.s_addr != sin->sin_addr.s_addr) {
        if (ipforward_rt.ro_rt) {
            RTFREE(ipforward_rt.ro_rt);
            ipforward_rt.ro_rt = 0;
        }
        sin->sin_family = AF_INET;
        sin->sin_len = sizeof(*sin);
        sin->sin_addr = ip->ip_dst;

        rtalloc(&ipforward_rt);
        if (ipforward_rt.ro_rt == 0) {
            icmp_error(m, ICMP_UNREACH, ICMP_UNREACH_HOST, dest, 0);
            return;
        }
        rt = ipforward_rt.ro_rt;
    }
    /*
     * Save at most 64 bytes of the packet in case
     * we need to generate an ICMP message to the src.
     */
    mcopy = m_copy(m, 0, imin((int) ip->ip_len, 64));

    ip_ifmatrix[rt->rt_ifp->if_index +
                if_index * m->m_pkthdr.rcvif->if_index]++;
```

ip_input.c

Figure 8.17 ip_forward function: route selection.

The question arises: How long is the longest path in the Internet? This metric is called the *diameter* of a network. There is no way to discover the diameter other than through empirical methods. A 37-hop path was posted in [Olivier 1994].

Decrement TTL

885–890 The packet identifier is converted back to network byte order since it isn't needed for forwarding and it should be in the correct order if ip_forward sends an ICMP error message, which includes the invalid IP header.

Net/3 neglects to convert ip_len, which ipintr converted to host byte order. The authors noted that on big endian machines this does not cause a problem since the bytes are never swapped. On little endian machines, such as a 386, this bug allows the byte-swapped value to be returned in the IP header within the ICMP error. This bug was observed in ICMP packets returned from SVR4 (probably Net/1 code) running on a 386 and from AIX 3.2 (4.3BSD Reno code).

If ip_ttl has reached 1 (IPTTLDEC), an ICMP time exceeded message is returned to the sender and the packet is discarded. Otherwise, ip_forward decrements ip_ttl by IPTTLDEC.

A system should never receive an IP datagram with a TTL of 0, but Net/3 generates the correct ICMP error if this happens since ip_ttl is examined after the packet is considered for local delivery and before it is forwarded.

Locate next hop

891–907 The IP forwarding algorithm caches the most recent route, in the global route structure ipforward_rt, and applies it to the current packet if possible. Research has shown that consecutive packets tend to have the same destination address ([Jain and Routhier 1986] and [Mogul 1991]), so this *one-behind* cache minimizes the number of routing lookups. If the cache (ipforward_rt) is empty or the current packet is to a different destination than the route entry in ipforward_rt, the previous route is discarded, ro_dst is initialized to the new destination, and rtalloc finds a route to the current packet's destination. If no route can be found for the destination, an ICMP host unreachable error is returned and the packed discarded.

908–914 Since ip_output discards the packet when an error occurs, m_copy makes a copy of the first 64 bytes in case ip_forward sends an ICMP error message. ip_forward does not abort if the call to m_copy fails. In this case, the error message is not sent. ip_ifmatrix records the number of packets routed between interfaces. The counter with the indexes of the receiving and sending interfaces is incremented.

Redirect Messages

A first-hop router returns an ICMP redirect message to the source host when the host incorrectly selects the router as the packet's first-hop destination. The IP networking model assumes that hosts are relatively ignorant of the overall internet topology and assigns the responsibility of maintaining correct routing tables to routers. A redirect message from a router informs a host that it has selected an incorrect route for a packet. We use Figure 8.18 to illustrate redirect messages.

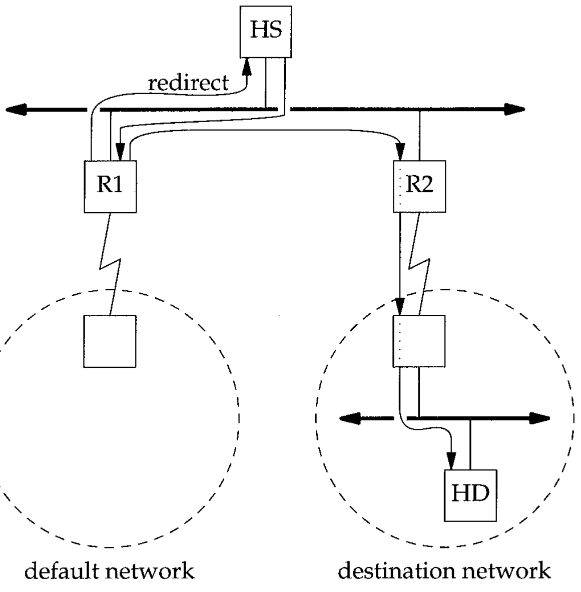


Figure 8.18 Router R1 is redirecting host HS to use router R2 to reach HD.

Generally, an administrator configures a host to send packets for remote networks to a default router. In Figure 8.18, host HS has R1 configured as its default router. When it first attempts to send a packet to HD it sends the packet to R1, not knowing that R2 is the appropriate choice. R1 recognizes the mistake, forwards the packet to R2, and sends a redirect message back to HS. After receiving the redirect, HS updates its routing tables so that the next packet to HD is sent directly to R2.

RFC 1122 recommends that only routers send redirect messages and that hosts must update their routing tables when receiving ICMP redirect messages (Section 11.8). Since Net/3 calls `ip_forward` only when the system is configured as a router, Net/3 follows RFC 1122's recommendations.

In Figure 8.19, `ip_forward` determines whether or not it should send a redirect message.

Leaving on receiving interface?

915–929 The rules by which a router recognizes redirect situations are complicated. First, redirects are applicable only when a packet is received and resent on the same interface (`rt_ifp` and `rcvif`). Next, the selected route must not have been itself created or modified by an ICMP redirect message (`RTF_DYNAMIC` | `RTF_MODIFIED`), nor can the route be to the default destination (0.0.0.0). This ensures that the system does not propagate routing information for which it is not an authoritative source, and that it does not share its default route with other systems.

ip_input.c

```
915     /*
916      * If forwarding packet is using same interface that it came in on,
917      * perhaps should send a redirect to sender to shortcut a hop.
918      * Only send redirect if source is sending directly to us,
919      * and if packet was not source routed (or has any options).
920      * Also, don't send redirect if forwarding using a default route
921      * or a route modified by a redirect.
922      */
923 #define satosin(sa) ((struct sockaddr_in *)(sa))
924     if (rt->rt_ifp == m->m_pkthdr.rcvif &&
925         (rt->rt_flags & (RTF_DYNAMIC | RTF_MODIFIED)) == 0 &&
926         satosin(rt_key(rt))->sin_addr.s_addr != 0 &&
927         ipsendredirects && !srcrt) {
928 #define RTA(rt) ((struct in_ifaddr *)(rt->rt_ifa))
929         u_long  src = ntohl(ip->ip_src.s_addr);

930         if (RTA(rt) &&
931             (src & RTA(rt)->ia_subnetmask) == RTA(rt)->ia_subnet) {
932             if (rt->rt_flags & RTF_GATEWAY)
933                 dest = satosin(rt->rt_gateway)->sin_addr.s_addr;
934             else
935                 dest = ip->ip_dst.s_addr;
936             /* Router requirements says to only send host redirects */
937             type = ICMP_REDIRECT;
938             code = ICMP_REDIRECT_HOST;
939         }
940     }
```

ip_input.c

Figure 8.19 ip_forward continued.

Generally, routing protocols use the special destination 0.0.0.0 to locate a default route. When a specific route to a destination is not available, the route associated with destination 0.0.0.0 directs the packet toward a default router.

Chapter 18 has more information about default routes.

The global integer ipsendredirects specifies whether the system has administrative authority to send redirects (Section 8.9). By default, ipsendredirects is 1. Redirects are suppressed when the system is source routing a packet as indicated by the srcrt argument passed to ip_forward, since presumably the source host wanted to override the decisions of the intermediate routers.

Send redirect?

930–931 This test determines if the packet originated on the local subnet. If the subnet mask bits of the source address and the outgoing interface's address are the same, the addresses are on the same IP network. If the source and the outgoing interface are on the same network, then this system should not have received the packet, since the source could have sent the packet directly to the correct first-hop router. The ICMP redirect message informs the host of the correct first-hop destination. If the packet originated on some other subnet, then the previous system was a router and this system does not send a redirect; the mistake will be corrected by a routing protocol.

In any case, routers are required to ignore redirect messages. Despite the requirement, Net/3 does not discard redirect messages when ipforwarding is set (i.e., when it is configured to be a router).

Select appropriate router

932–940 The ICMP redirect message contains the address of the correct next system, which is a router's address if the destination host is not on the directly connected network or the host address if the destination host is on the directly connected network.

RFC 792 describes four types of redirect messages: (1) network, (2) host, (3) TOS and network, and (4) TOS and host. RFC 1009 recommends against sending network redirects at any time because of the impossibility of guaranteeing that the host receiving the redirect can determine the appropriate subnet mask for the destination network. RFC 1122 recommends that hosts treat network redirects as host redirects to avoid this ambiguity. Net/3 sends only host redirects and ignores any TOS considerations. In Figure 8.20, `ipintr` passes the packet and any ICMP messages to the link layer.

The redirect messages were standardized before subnetting. In a nonsubnetted internet, network redirects are useful but in a subnetted internet they are ambiguous since they do not include a subnet mask.

Forward packet

941–954 At this point, `ip_forward` has a route for the packet and has determined if an ICMP redirect is warranted. `ip_output` sends the packet to the next hop as specified in the route `ipforward_rt`. The `IP_ALLOWBROADCAST` flag allows the packet being forwarded to be a directed broadcast to a local network. If `ip_output` succeeds and no redirect message needs to be sent, the copy of the first 64 bytes of the packet is discarded and `ip_forward` returns.

Send ICMP error?

955–983 `ip_forward` may need to send an ICMP message because `ip_output` failed or a redirect is pending. If there is no copy of the original packet (there might have been a buffer shortage at the time the copy was attempted), the message can't be sent and `ip_forward` returns. If a redirect is pending, `type` and `code` have been previously set, but if `ip_output` failed, the `switch` statement sets up the new ICMP type and code values based on the return value from `ip_output`. `icmp_error` sends the message. The ICMP message from a failed `ip_output` overrides any pending redirect message.

It is important to recognize the significance of the `switch` statement that handles errors from `ip_output`. It translates local system errors into the appropriate ICMP error message, which is returned to the packet's source. Figure 8.21 summarizes the errors. Chapter 11 describes the ICMP messages in more detail.

Net/3 always generates the ICMP source quench when `ip_output` returns `ENOBUFS`. The Router Requirements RFC [Almquist and Kastenholz 1994] deprecate the source quench and state that a router should not generate them.

ip_input.c

```
    error = ip_output(m, (struct mbuf *) 0, &ipforward_rt,
                      IP_FORWARDING | IP_ALLOWBROADCAST, 0);
    if (error)
        ipstat.ips_cantforward++;
    else {
        ipstat.ips_forward++;
        if (type)
            ipstat.ips_redirectsent++;
        else {
            if (mcopy)
                m_freem(mcopy);
            return;
        }
    }
    if (mcopy == NULL)
        return;
    destifp = NULL;

    switch (error) {

    case 0:                 /* forwarded, but need redirect */
        /* type, code set above */
        break;

    case ENETUNREACH:           /* shouldn't happen, checked above */
    case EHOSTUNREACH:
    case ENETDOWN:
    case EHOSTDOWN:
    default:
        type = ICMP_UNREACH;
        code = ICMP_UNREACH_HOST;
        break;

    case EMSGSIZE:
        type = ICMP_UNREACH;
        code = ICMP_UNREACH_NEEDFRAG;
        if (ipforward_rt.ro_rt)
            destifp = ipforward_rt.ro_rt->rt_ifp;
        ipstat.ips_cantfrag++;
        break;

    case ENOBUFS:
        type = ICMP_SOURCEQUENCH;
        code = 0;
        break;
    }
    icmp_error(mcopy, type, code, dest, destifp);
}
```

ip_input.c

Figure 8.20 ip_forward continued.

Error code from ip_output	ICMP message generated	Description
EMSGSIZE	ICMP_UNREACH_NEEDFRAG	The outgoing packet was too large for the selected interface and fragmentation was prohibited (Chapter 10).
ENOBUFS	ICMP_SOURCEQUENCH	The interface queue is full or the kernel is running short of free memory. This message is an indication to the source host to lower the data rate.
EHOSTUNREACH		A route to the host could not be found.
ENETDOWN		The outgoing interface specified by the route is not operating.
EHOSTDOWN	ICMP_UNREACH_HOST	The interface could not send the packet to the selected host.
default		Any unrecognized error is reported as an ICMP_UNREACH_HOST error.

Figure 8.21 Errors from ip_output.

8.6 Output Processing: ip_output Function

The IP output code receives packets from two sources: ip_forward and the transport protocols (Figure 8.1). It would seem reasonable to expect IP output operations to be accessed by inetsw[0].pr_output, but this is not the case. The standard Internet transport protocols (ICMP, IGMP, UDP, and TCP) call ip_output directly instead of going through the inetsw table. For the standard Internet transport protocols, the generality of the protosw structure is not necessary, since the calling functions are not accessing IP in a protocol-independent context. In Chapter 20 we'll see that the protocol-independent routing sockets call pr_output to access IP.

We describe ip_output in three sections:

- header initialization,
- route selection, and
- source address selection and fragmentation.

Header Initialization

The first section of ip_output, shown in Figure 8.22, merges options into the outgoing packet and completes the IP header for packets that are passed from the transport protocols (not those from ip_forward).

44–59 The arguments to ip_output are: m0, the packet to send; opt, the IP options to include; ro, a cached route to the destination; flags, described in Figure 8.23; and imo, a pointer to multicast options described in Chapter 12.

IP_FORWARDING is set by ip_forward and ip_mforward (multicast packet forwarding) and prevents ip_output from resetting any of the IP header fields.

ip_output.c

```
int
ip_output(m0, opt, ro, flags, imo)
struct mbuf *m0;
struct mbuf *opt;
struct route *ro;
int     flags;
struct ip_moptions *imo;
{
    struct ip *ip, *mhip;
    struct ifnet *ifp;
    struct mbuf *m = m0;
    int     hlen = sizeof(struct ip);
    int     len, off, error = 0;
    struct route iproute;
    struct sockaddr_in *dst;
    struct in_ifaddr *ia;

    if (opt) {
        m = ip_insertoptions(m, opt, &len);
        hlen = len;
    }
    ip = mtod(m, struct ip *);
    /*
     * Fill in IP header.
     */
    if ((flags & (IP_FORWARDING | IP_RAWOUTPUT)) == 0) {
        ip->ip_v = IPVERSION;
        ip->ip_off &= IP_DF;
        ip->ip_id = htons(ip_id++);
        ip->ip_hl = hlen >> 2;
        ipstat.ips_localout++;
    } else {
        hlen = ip->ip_hl << 2;
    }
```

ip_output.c

Figure 8.22 ip_output function.

Flag	Description
IP_FORWARDING	This is a forwarded packet.
IP_ROUTETOIF	Ignore routing tables and route directly to interface.
IP_ALLOWBROADCAST	Allow broadcast packets to be sent.
IP_RAWOUTPUT	Packet contains a preconstructed IP header.

Figure 8.23 ip_output: flag values.

The MSG_DONTROUTE flag to send, sendto, and sendmsg enables IP_ROUTETOIF for a single write (Section 16.4) while the SO_DONTROUTE socket option enables IP_ROUTETOIF for *all* writes on a particular socket (Section 8.8). The flag is passed by each of the transport protocols to ip_output.

The IP_ALLOWBROADCAST flag can be set by the SO_BROADCAST socket option (Section 8.8) but is passed only by UDP. The raw IP protocol sets IP_ALLOWBROADCAST by default. TCP does not support broadcasts, so IP_ALLOWBROADCAST is not passed by TCP to ip_output. There is no per-request flag for broadcasting.

Construct IP header

60–73 If the caller provides any IP options they are merged with the packet by ip_insertoptions (Section 9.8), which returns the new header length.

We'll see in Section 8.8 that a process can set the IP_OPTIONS socket option to specify the IP options for a socket. The transport layer for the socket (TCP or UDP) always passes these options to ip_output.

The IP header of a forwarded packet (IP_FORWARDING) or a packet with a preconstructed header (IP_RAWOUTPUT) should not be modified by ip_output. Any other packet (e.g., a UDP or TCP packet that originates at this host) needs to have several IP header fields initialized. ip_output sets ip_v to 4 (IPVERSION), clears ip_off except for the DF bit, which is left as provided by the caller (Chapter 10), and assigns a unique identifier to ip->ip_id from the global integer ip_id, which is immediately incremented. Remember that ip_id was seeded from the system clock during protocol initialization (Section 7.8). ip_hl is set to the header length measured in 32-bit words.

Most of the remaining fields in the IP header—length, offset, TTL, protocol, TOS, and the destination address—have already been initialized by the transport protocol. The source address may not be set, in which case it is selected after a route to the destination has been located (Figure 8.25).

Packet already includes header

74–76 For a forwarded packet (or a raw IP packet with a header), the header length (in bytes) is saved in hlen for use by the fragmentation algorithm.

Route Selection

After completing the IP header, the next task for ip_output is to locate a route to the destination. This is shown in Figure 8.24.

ip_output.c

```
    /*
     * Route packet.
     */
    if (ro == 0) {
        ro = &iproute;
        bzero((caddr_t) ro, sizeof(*ro));
    }
    dst = (struct sockaddr_in *) &ro->ro_dst;
    /*
     * If there is a cached route,
     * check that it is to the same destination
     * and is still up.  If not, free it and try again.
     */
```

```
 90     if (ro->ro_rt && ((ro->ro_rt->rt_flags & RTF_UP) == 0 ||
 91                       dst->sin_addr.s_addr != ip->ip_dst.s_addr)) {
 92         RTFREE(ro->ro_rt);
 93         ro->ro_rt = (struct rtentry *) 0;
 94     }
 95     if (ro->ro_rt == 0) {
 96         dst->sin_family = AF_INET;
 97         dst->sin_len = sizeof(*dst);
 98         dst->sin_addr = ip->ip_dst;
 99     }
100     /*
101      * If routing to interface only,
102      * short circuit routing lookup.
103      */
104 #define ifatoia(ifa)    ((struct in_ifaddr *)(ifa))
105 #define sintosa(sin)    ((struct sockaddr *)(sin))
106     if (flags & IP_ROUTETOIF) {
107         if ((ia = ifatoia(ifa_ifwithdstaddr(sintosa(dst)))) == 0 &&
108             (ia = ifatoia(ifa_ifwithnet(sintosa(dst)))) == 0) {
109             ipstat.ips_noroute++;
110             error = ENETUNREACH;
111             goto bad;
112         }
113         ifp = ia->ia_ifp;
114         ip->ip_ttl = 1;
115     } else {
116         if (ro->ro_rt == 0)
117             rtalloc(ro);
118         if (ro->ro_rt == 0) {
119             ipstat.ips_noroute++;
120             error = EHOSTUNREACH;
121             goto bad;
122         }
123         ia = ifatoia(ro->ro_rt->rt_ifa);
124         ifp = ro->ro_rt->rt_ifp;
125         ro->ro_rt->rt_use++;
126         if (ro->ro_rt->rt_flags & RTF_GATEWAY)
127             dst = (struct sockaddr_in *) ro->ro_rt->rt_gateway;
128     }

                    /* multicast destination (Figure 12.40) */
```

ip_output.c

Figure 8.24 ip_output continued.

Verify cached route

77–99 A cached route may be provided to ip_output as the ro argument. In Chapter 24 we'll see that UDP and TCP maintain a route cache associated with each socket. If a route has not been provided, ip_output sets ro to point to the temporary route structure iproute.

If the cached destination is not to the current packet's destination, the route is discarded and the new destination address placed in dst.

Bypass routing

100–114 A caller can prevent packet routing by setting the IP_ROUTETOIF flag (Section 8.8). If this flag is set, ip_output must locate an interface directly connected to the destination network specified in the packet. ifa_ifwithdstaddr searches point-to-point interfaces, while in_ifwithnet searches all the others. If neither function finds an interface connected to the destination network, ENETUNREACH is returned; otherwise, ifp points to the selected interface.

This option allows routing protocols to bypass the local routing tables and force the packets to exit the system by a particular interface. In this way, routing information can be exchanged with other routers even when the local routing tables are incorrect.

Locate route

115–122 If the packet is being routed (IP_ROUTETOIF is off) and there is no cached route, rtalloc locates a route to the address specified by dst. ip_output returns EHOSTUNREACH if rtalloc fails to find a route. If ip_forward called ip_output, EHOSTUNREACH is converted to an ICMP error. If a transport protocol called ip_output, the error is passed back to the process (Figure 8.21).

123–128 ia is set to point to an address (the ifaddr structure) of the selected interface and ifp points to the interface's ifnet structure. If the next hop is not the packet's final destination, dst is changed to point to the next-hop router instead of the packet's final destination. The destination address within the IP header remains unchanged, but the interface layer must deliver the packet to dst, the next-hop router.

Source Address Selection and Fragmentation

The final section of ip_output, shown in Figure 8.25, ensures that the IP header has a valid source address and then passes the packet to the interface associated with the route. If the packet is larger than the interface's MTU, it must be fragmented and transmitted in pieces. As we did with the reassembly code, we omit the fragmentation code here and postpone discussion of it until Chapter 10.

ip_output.c

```
    /*
     * If source address not specified yet, use address
     * of outgoing interface.
     */
    if (ip->ip_src.s_addr == INADDR_ANY)
        ip->ip_src = IA_SIN(ia)->sin_addr;
    /*
     * Look for broadcast address and
     * verify user is allowed to send
     * such a packet.
     */
```

```
223     if (in_broadcast(dst->sin_addr, ifp)) {
224         if ((ifp->if_flags & IFF_BROADCAST) == 0) {     /* interface check */
225             error = EADDRNOTAVAIL;
226             goto bad;
227         }
228         if ((flags & IP_ALLOWBROADCAST) == 0) {     /* application check */
229             error = EACCES;
230             goto bad;
231         }
232         /* don't allow broadcast messages to be fragmented */
233         if ((u_short) ip->ip_len > ifp->if_mtu) {
234             error = EMSGSIZE;
235             goto bad;
236         }
237         m->m_flags |= M_BCAST;
238     } else
239         m->m_flags &= ~M_BCAST;

240   sendit:
241     /*
242      * If small enough for interface, can just send directly.
243      */
244     if ((u_short) ip->ip_len <= ifp->if_mtu) {
245         ip->ip_len = htons((u_short) ip->ip_len);
246         ip->ip_off = htons((u_short) ip->ip_off);
247         ip->ip_sum = 0;
248         ip->ip_sum = in_cksum(m, hlen);
249         error = (*ifp->if_output) (ifp, m,
250                                    (struct sockaddr *) dst, ro->ro_rt);
251         goto done;
252     }

                           /* fragmentation (Section 10.3) */

339   done:
340     if (ro == &iproute && (flags & IP_ROUTETOIF) == 0 && ro->ro_rt)
341         RTFREE(ro->ro_rt);
342     return (error);
343   bad:
344     m_freem(m0);
345     goto done;
346 }
```
ip_output.c

Figure 8.25 ip_output continued.

Select source address

212–239 If `ip_src` has not been specified, then `ip_output` selects `ia`, the IP address of the outgoing interface, as the source address. This couldn't be done earlier when the other IP header fields were filled in because a route hadn't been selected yet. Forwarded packets always have a source address, but packets that originate at the local host may not if the sending process has not explicitly selected one.

If the destination IP address is a broadcast address, the interface must support broadcasting (IFF_BROADCAST, Figure 3.7), the caller must explicitly enable broadcasting (IP_ALLOWBROADCAST, Figure 8.23), and the packet must be small enough to be sent without fragmentation.

This last test is a policy decision. Nothing in the IP protocol specification explicitly prohibits the fragmentation of broadcast packets. By requiring the packet to fit within the MTU of the interface, however, there is an increased chance that the broadcast packet will be received at every interface, because there is a better chance of receiving one undamaged packet than of receiving two or more undamaged packets.

If any of these conditions are not met, the packet is dropped and EADDRNOTAVAIL, EACCES, or EMSGSIZE is returned to the caller. Otherwise, M_BCAST is set on the outgoing packet, which tells the interface output function to send the packet as a link-level broadcast. In Section 21.10 we'll see that arpresolve translates the IP broadcast address to the Ethernet broadcast address.

If the destination address is not a broadcast address, ip_output clears M_BCAST.

If M_BCAST were not cleared, the reply to a request packet that arrived as a broadcast might be accidentally returned as a broadcast. We'll see in Chapter 11 that ICMP replies are constructed within the request packet in this way as are TCP RST packets (Section 26.9).

Send packet

240–252 If the packet is small enough for the selected interface, ip_len and ip_off are converted to network byte order, the IP checksum is computed with in_cksum (Section 8.7), and the packet is passed to the if_output function of the selected interface.

Fragment packet

253–338 Larger packets must be fragmented before they can be sent. We have omitted that code here and describe it in Chapter 10 instead.

Cleanup

339–346 A reference count is maintained for the route entries. Recall that ip_output may use a temporary route structure (iproute) if the argument ro is null. If necessary, RTFREE releases the route entry within iproute and decrements the reference count. The code at bad discards the current packet before returning.

Reference counting is a memory management technique. The programmer must count the number of external references to a data structure; when the count returns to 0, the memory can be safely returned to the free pool. Reference counting requires some discipline by the programmer, who must explicitly increase and decrease the reference count when appropriate.

8.7 Internet Checksum: in_cksum Function

Two operations dominate the time required to process packets: copying the data and computing checksums ([Kay and Pasquale 1993]). The flexible nature of the mbuf data structure is the primary method of reducing copy operations in Net/3. Efficient computing of checksums is harder since it is very hardware dependent. Net/3 contains several implementations of in_cksum.

Version	Source file
portable C	sys/netinet/in_cksum.c
SPARC	net3/sparc/sparc/in_cksum.c
68k	net3/luna68k/luna68k/in_cksum.c
VAX	sys/vax/vax/in_cksum.c
Tahoe	sys/tahoe/tahoe/in_cksum.c
HP 3000	sys/hp300/hp300/in_cksum.c
Intel 80386	sys/i386/i386/in_cksum.c

Figure 8.26 in_cksum versions in Net/3.

Even the portable C implementation has been optimized considerably. RFC 1071 [Braden, Borman, and Partridge 1988] and RFC 1141 [Mallory and Kullberg 1990] discuss the design and implementation of the Internet checksum function. RFC 1141 has been updated by RFC 1624 [Rijsinghani 1994]. From RFC 1071:

1. Adjacent bytes to be checksummed are paired to form 16-bit integers, and the one's complement sum of these 16-bit integers is formed.
2. To generate a checksum, the checksum field itself is cleared, the 16-bit one's complement sum is computed over the bytes concerned, and the one's complement of this sum is placed in the checksum field.
3. To verify a checksum, the one's complement sum is computed over the same set of bytes, including the checksum field. If the result is all 1 bits (–0 in one's complement arithmetic, as explained below), the check succeeds.

Briefly, when addition is performed on integers in one's complement representation, the result is obtained by summing the two integers and adding any carry bit to the result to obtain the final sum. In one's complement arithmetic the negative of a number is formed by complementing each bit. There are two representations of 0 in one's complement arithmetic: all 0 bits, and all 1 bits. A more detailed discussion of one's complement representations and arithmetic can be found in [Mano 1982].

The checksum algorithm computes the value to place in the checksum field of the IP header before sending the packet. To compute this value, the checksum field in the header is set to 0 and the one's complement sum on the entire header (including options) is computed. The header is processed as an array of 16-bit integers. Let's call the result of this computation a. Since the checksum field is explicitly set to 0, a is also the sum of all the IP header fields except the checksum. The one's complement of a, denoted $-a$, is placed in the checksum field and the packet is sent.

If no bits are altered in transit, the computed checksum at the destination should be the complement of $(a + -a)$. The sum $(a + -a)$ in one's complement arithmetic is –0 (all 1 bits) and its complement is 0 (all 0 bits). So the computed checksum of an undamaged packet at the destination should always be 0. This is what we saw in Figure 8.12. The following C code (which is not part of Net/3) is a naive implementation of this algorithm:

```
 1 unsigned short
 2 cksum(struct ip *ip, int len)
 3 {
 4     long    sum = 0;           /* assume 32 bit long, 16 bit short */

 5     while (len > 1) {
 6         sum += *((unsigned short *) ip)++;
 7         if (sum & 0x80000000)    /* if high-order bit set, fold */
 8             sum = (sum & 0xFFFF) + (sum >> 16);
 9         len -= 2;
10     }

11     if (len)                   /* take care of left over byte */
12         sum += (unsigned short) *(unsigned char *) ip;

13     while (sum >> 16)
14         sum = (sum & 0xFFFF) + (sum >> 16);

15     return ~sum;
16 }
```

Figure 8.27 A naive implementation of the IP checksum calculation.

1–16 The only performance enhancement here is to accumulate the carry bits in the high-order 16 bits of sum. The accumulated carries are added to the low-order 16 bits when the loop terminates, until no more carries occur. RFC 1071 calls this *deferred carries*. This technique is useful on machines that don't have an add-with-carry instruction or when detecting a carry is expensive.

Now we show the portable C version from Net/3. It utilizes the deferred carry technique and works with packets stored in an mbuf chain.

42–140 Our naive checksum implementation assumed that all the bytes to be checksummed were in a contiguous buffer instead of in mbuf chains. This version of the checksum calculation handles the mbufs correctly using the same underlying algorithm: 16-bit words are summed in a 32-bit integer with the carries deferred. For mbufs with an odd number of bytes, the extra byte is saved and paired with the first byte of the next mbuf. Since unaligned access to 16-bit words is invalid or incurs a severe performance penalty on most architectures, a misaligned byte is saved and in_cksum continues adding with the next aligned word. in_cksum is careful to byte swap the sum when this occurs to ensure that even-numbered and odd-numbered data bytes are collected in separate sum bytes as required by the checksum algorithm.

Loop unrolling

93–115 The three while loops in the function add 16 words, 4 words, and 1 word to the sum during each iteration. The unrolled loops reduce the loop overhead and can be considerably faster than a straightforward loop on some architectures. The price is increased code size and complexity.

in_cksum.c

```
#define ADDCARRY(x)  (x > 65535 ? x -= 65535 : x)
#define REDUCE {l_util.l = sum; sum = l_util.s[0] + l_util.s[1]; ADDCARRY(sum);}
int
in_cksum(m, len)
struct mbuf *m;
int     len;
{
    u_short *w;
    int     sum = 0;
    int     mlen = 0;
    int     byte_swapped = 0;
    union {
        char    c[2];
        u_short s;
    } s_util;
    union {
        u_short s[2];
        long    l;
    } l_util;
    for (; m && len; m = m->m_next) {
        if (m->m_len == 0)
            continue;
        w = mtod(m, u_short *);
        if (mlen == -1) {
            /*
             * The first byte of this mbuf is the continuation of a
             * word spanning between this mbuf and the last mbuf.
             *
             * s_util.c[0] is already saved when scanning previous mbuf.
             */
            s_util.c[1] = *(char *) w;
            sum += s_util.s;
            w = (u_short *) ((char *) w + 1);
            mlen = m->m_len - 1;
            len--;
        } else
            mlen = m->m_len;
        if (len < mlen)
            mlen = len;
        len -= mlen;
        /*
         * Force to even boundary.
         */
        if ((1 & (int) w) && (mlen > 0)) {
            REDUCE;
            sum <<= 8;
            s_util.c[0] = *(u_char *) w;
            w = (u_short *) ((char *) w + 1);
            mlen--;
            byte_swapped = 1;
        }
        /*
         * Unroll the loop to make overhead from
         * branches &c small.
         */
        while ((mlen -= 32) >= 0) {
            sum += w[0]; sum += w[1]; sum += w[2]; sum += w[3];
            sum += w[4]; sum += w[5]; sum += w[6]; sum += w[7];
            sum += w[8]; sum += w[9]; sum += w[10]; sum += w[11];
            sum += w[12]; sum += w[13]; sum += w[14]; sum += w[15];
            w += 16;
        }
        mlen += 32;
        while ((mlen -= 8) >= 0) {
            sum += w[0]; sum += w[1]; sum += w[2]; sum += w[3];
            w += 4;
        }
        mlen += 8;
        if (mlen == 0 && byte_swapped == 0)
            continue;
        REDUCE;
        while ((mlen -= 2) >= 0) {
            sum += *w++;
        }
        if (byte_swapped) {
            REDUCE;
            sum <<= 8;
            byte_swapped = 0;
            if (mlen == -1) {
                s_util.c[1] = *(char *) w;
                sum += s_util.s;
                mlen = 0;
            } else
                mlen = -1;
        } else if (mlen == -1)
            s_util.c[0] = *(char *) w;
    }
    if (len)
        printf("cksum: out of data\n");
    if (mlen == -1) {
        /* The last mbuf has odd # of bytes. Follow the standard (the odd
           byte may be shifted left by 8 bits or not as determined by
           endian-ness of the machine) */
        s_util.c[1] = 0;
        sum += s_util.s;
    }
    REDUCE;
    return (~sum & 0xffff);
}
```

in_cksum.c

Figure 8.28 An optimized portable C implementation of the IP checksum calculation.

More Optimizations

RFC 1071 mentions two optimizations that don't appear in Net/3: a combined copy-with-checksum operation and incremental checksum updates. Merging the copy and checksum operations is not as important for the IP header checksum as it is for the TCP and UDP checksums, which cover many more bytes. This merged operation is discussed in Section 23.12. [Partridge and Pink 1993] report that an inline version of the IP header checksum is faster than calling the more general in_cksum function and can be done in six to eight assembler instructions (for the standard 20-byte IP header).

The design of the checksum algorithm allows a packet to be changed and the checksum updated without reexamining all the bytes. RFC 1071 contains a brief discussion of this topic. RFCs 1141 and 1624 contain more detailed discussions. A typical use of this technique occurs during packet forwarding. In the common case, when a packet has no options, only the TTL field changes during forwarding. The checksum in this case can be recomputed by a single addition with an end-around carry.

In addition to being more efficient, an incremental checksum can help detect headers corrupted by buggy software. A corrupted header is detected by the next system if the checksum is computed incrementally, but if it is recomputed from scratch, the checksum incorporates the erroneous bytes and the corrupted header is not detected by the next system. The end-to-end checksum used by UDP or TCP detects the error at the final destination. We'll see in Chapters 23 and 25 that the UDP and TCP checksums incorporate several parts of the IP header.

For an example of the checksum function that utilizes hardware add-with-carry instructions to compute the checksum 32 bits at a time, see the VAX implementation of in_cksum in the file ./sys/vax/vax/in_cksum.c.

8.8 setsockopt and getsockopt System Calls

Net/3 provides access to several networking features through the setsockopt and getsockopt system calls. These system calls support a generic interface used by a process to access features of a networking protocol that aren't supported by the standard system calls. The prototypes for these two calls are:

```
int setsockopt(int s, int level, int optname, const void *optval, int optlen);

int getsockopt(int s, int level, int optname, void *optval, int *optlen);
```

Most socket options affect only the socket on which they are issued. Compare this to sysctl parameters, which affect the entire system. The socket options associated with multicasting are a notable exception and are described in Chapter 12.

setsockopt and getsockopt set and get options at all levels of the communication stack. Net/3 processes options according to the protocol associated with *s* and the identifier specified by *level*. Figure 8.29 lists possible values for *level* within the protocols that we discuss.

We describe the implementation of the setsockopt and getsockopt system calls in Chapter 17, but we discuss the implementation of individual options within the

Domain	Protocol	*level*	Function	Reference
any	any	*SOL_SOCKET*	sosetopt and sogetopt	Figures 17.5 and 17.11
IP	UDP	*IPPROTO_IP*	ip_ctloutput	Figure 8.31
	TCP	*IPPROTO_TCP* *IPPROTO_IP*	tcp_ctloutput ip_ctloutput	Section 30.6 Figure 8.31
	raw IP ICMP IGMP	*IPPROTO_IP*	rip_ctloutput and ip_ctloutput	Section 32.8

Figure 8.29 setsockopt and getsockopt arguments.

optname	*optval* type	Function	Description
IP_OPTIONS	void *	in_pcbopts	set or get IP options to be included in outgoing datagrams
IP_TOS	int	ip_ctloutput	set or get IP TOS for outgoing datagrams
IP_TTL	int	ip_ctloutput	set or get IP TTL for outgoing datagrams
IP_RECVDSTADDR	int	ip_ctloutput	enable or disable queueing of IP destination address (UDP only)
IP_RECVOPTS	int	ip_ctloutput	enable or disable queueing of incoming IP options as control information (UDP only, not implemented)
IP_RECVRETOPTS	int	ip_ctloutput	enable or disable queueing of reversed source route associated with incoming datagram (UDP only, not implemented)

Figure 8.30 Socket options: IPPROTO_IP level for SOCK_RAW, SOCK_DGRAM, or SOCK_STREAM sockets.

appropriate chapters. In this chapter, we cover the options that provide access to IP features.

Throughout the text we summarize socket options as shown in Figure 8.30. This figure shows the options for the IPPROTO_IP level. The option appears in the first column, the data type of the variable pointed to by *optval* appears in the second column, and the third column shows the function that processes the option.

Figure 8.31 shows the overall organization of the ip_ctloutput function, which handles most of the IPPROTO_IP options. In Section 32.8 we show the additional IPPROTO_IP options that work with SOCK_RAW sockets.

431–447 ip_ctloutput's first argument, op, is either PRCO_SETOPT or PRCO_GETOPT. The second argument, so, points to the socket on which the request was issued. level must be IPPROTO_IP. optname is the option to change or to retrieve, and mp points indirectly to an mbuf that contains the related data for the option. m is initialized to point to the mbuf referenced by *mp.

448–500 If an unrecognized option is specified in the call to setsockopt (and therefore to the PRCO_SETOPT case of the switch), ip_ctloutput releases any mbuf passed by the caller and returns EINVAL.

ip_output.c

```
431 int
432 ip_ctloutput(op, so, level, optname, mp)
433 int     op;
434 struct socket *so;
435 int     level, optname;
436 struct mbuf **mp;
437 {
438     struct inpcb *inp = sotoinpcb(so);
439     struct mbuf *m = *mp;
440     int     optval;
441     int     error = 0;

442     if (level != IPPROTO_IP) {
443         error = EINVAL;
444         if (op == PRCO_SETOPT && *mp)
445             (void) m_free(*mp);
446     } else
447         switch (op) {

448         case PRCO_SETOPT:
449             switch (optname) {

                    /* PRCO_SETOPT processing (Figures 8.32 and 12.17) */

493               freeit:
494             default:
495                 error = EINVAL;
496                 break;
497             }
498             if (m)
499                 (void) m_free(m);
500             break;

501         case PRCO_GETOPT:
502             switch (optname) {

                    /* PRCO_GETOPT processing (Figures 8.33 and 12.17) */

546             default:
547                 error = ENOPROTOOPT;
548                 break;
549             }
550             break;
551         }
552     return (error);
553 }
```

ip_output.c

Figure 8.31 ip_ctloutput function: overview.

501–553 Unrecognized options passed to getsockopt result in ip_ctloutput returning ENOPROTOOPT. In this case, the caller releases the mbuf.

PRCO_SETOPT Processing

The processing for PRCO_SETOPT is shown in Figure 8.32.

ip_output.c
```
450             case IP_OPTIONS:
451                 return (ip_pcbopts(&inp->inp_options, m));

452             case IP_TOS:
453             case IP_TTL:
454             case IP_RECVOPTS:
455             case IP_RECVRETOPTS:
456             case IP_RECVDSTADDR:
457                 if (m->m_len != sizeof(int))
458                             error = EINVAL;
459                 else {
460                     optval = *mtod(m, int *);
461                     switch (optname) {

462                     case IP_TOS:
463                         inp->inp_ip.ip_tos = optval;
464                         break;

465                     case IP_TTL:
466                         inp->inp_ip.ip_ttl = optval;
467                         break;
468 #define OPTSET(bit) \
469     if (optval) \
470         inp->inp_flags |= bit; \
471     else \
472         inp->inp_flags &= ~bit;

473                     case IP_RECVOPTS:
474                         OPTSET(INP_RECVOPTS);
475                         break;

476                     case IP_RECVRETOPTS:
477                         OPTSET(INP_RECVRETOPTS);
478                         break;

479                     case IP_RECVDSTADDR:
480                         OPTSET(INP_RECVDSTADDR);
481                         break;
482                     }
483                 }
484                 break;
```
ip_output.c

Figure 8.32 ip_ctloutput function: PRCO_SETOPT processing.

450–451 IP_OPTIONS is processed by ip_pcbopts (Figure 9.32).

452–484 The IP_TOS, IP_TTL, IP_RECVOPTS, IP_RECVRETOPTS, and IP_RECVDSTADDR options all expect an integer to be available in the mbuf pointed to by m. The integer is stored in optval and then used to change the ip_tos or ip_ttl values associated with the socket or to set or clear the INP_RECVOPTS, INP_RECVRETOPTS, or INP_RECVDSTADDR flags associated with the socket. The macro OPTSET sets (or clears) the specified bit if optval is nonzero (or 0).

Figure 8.30 showed that IP_RECVOPTS and IP_RECVRETOPTS were not implemented. In Chapter 23, we'll see that the settings of these options are ignored by UDP.

PRCO_GETOPT Processing

Figure 8.32 shows the code that retrieves the IP options when PRCO_GETOPT is specified.

ip_output.c

```
503             case IP_OPTIONS:
504                 *mp = m = m_get(M_WAIT, MT_SOOPTS);
505                 if (inp->inp_options) {
506                     m->m_len = inp->inp_options->m_len;
507                     bcopy(mtod(inp->inp_options, caddr_t),
508                           mtod(m, caddr_t), (unsigned) m->m_len);
509                 } else
510                     m->m_len = 0;
511                 break;

512             case IP_TOS:
513             case IP_TTL:
514             case IP_RECVOPTS:
515             case IP_RECVRETOPTS:
516             case IP_RECVDSTADDR:
517                 *mp = m = m_get(M_WAIT, MT_SOOPTS);
518                 m->m_len = sizeof(int);
519                 switch (optname) {

520                 case IP_TOS:
521                     optval = inp->inp_ip.ip_tos;
522                     break;

523                 case IP_TTL:
524                     optval = inp->inp_ip.ip_ttl;
525                     break;

526 #define OPTBIT(bit) (inp->inp_flags & bit ? 1 : 0)

527                 case IP_RECVOPTS:
528                     optval = OPTBIT(INP_RECVOPTS);
529                     break;

530                 case IP_RECVRETOPTS:
531                     optval = OPTBIT(INP_RECVRETOPTS);
532                     break;

533                 case IP_RECVDSTADDR:
534                     optval = OPTBIT(INP_RECVDSTADDR);
535                     break;
536                 }
537                 *mtod(m, int *) = optval;
538                 break;
```

ip_output.c

Figure 8.33 ip_ctloutput function: PRCO_GETOPT processing.

503–538 For IP_OPTIONS, ip_ctloutput returns an mbuf containing a copy of the options associated with the socket. For the remaining options, ip_ctloutput returns the value of ip_tos, ip_ttl, or the state of the flag associated with the option. The value is returned in the mbuf pointed to by m. The macro OPTBIT returns 1 (or 0) if bit is on (or off) in inp_flags.

Notice that the IP options are stored in the protocol control block (inp, Chapter 22) associated with the socket.

8.9 ip_sysctl Function

Figure 7.27 showed that the ip_sysctl function is called when the protocol and family identifiers are 0 in a call to sysctl. Figure 8.34 shows the three parameters supported by ip_sysctl.

sysctl constant	Net/3 variable	Description
IPCTL_FORWARDING	ipforwarding	Should the system forward IP packets?
IPCTL_SENDREDIRECTS	ipsendredirects	Should the system send ICMP redirects?
IPCTL_DEFTTL	ip_defttl	Default TTL for IP packets.

Figure 8.34 ip_sysctl parameters.

Figure 8.35 shows the ip_sysctl function.

ip_input.c

```
int
ip_sysctl(name, namelen, oldp, oldlenp, newp, newlen)
int     *name;
u_int    namelen;
void    *oldp;
size_t *oldlenp;
void    *newp;
size_t  newlen;
{
    /* All sysctl names at this level are terminal. */
    if (namelen != 1)
        return (ENOTDIR);

    switch (name[0]) {
    case IPCTL_FORWARDING:
        return (sysctl_int(oldp, oldlenp, newp, newlen, &ipforwarding));
    case IPCTL_SENDREDIRECTS:
        return (sysctl_int(oldp, oldlenp, newp, newlen,
                           &ipsendredirects));
    case IPCTL_DEFTTL:
        return (sysctl_int(oldp, oldlenp, newp, newlen, &ip_defttl));
    default:
        return (EOPNOTSUPP);
    }
    /* NOTREACHED */
}
```

ip_input.c

Figure 8.35 ip_sysctl function.

984–995 Since ip_sysctl does not forward sysctl requests to any other functions, there can be only one remaining component in name. If not, ENOTDIR is returned.

996–1008 The switch statement selects the appropriate call to sysctl_int, which accesses or modifies ipforwarding, ipsendredirects, or ip_defttl. EOPNOTSUPP is returned for unrecognized options.

8.10 Summary

IP is a best-effort datagram service that provides the delivery mechanism for all other Internet protocols. The standard IP header is 20 bytes long, but may be followed by up to 40 bytes of options. IP can split large datagrams into fragments to be transmitted and reassembles the fragments at the final destination. Option processing is discussed in Chapter 9, and fragmentation and reassembly is discussed in Chapter 10.

ipintr ensures that IP headers have arrived undamaged and determines if they have arrived at their final destination by comparing the destination address to the IP addresses of the system's interfaces and to several broadcast addresses. ipintr passes datagrams that have reached their final destination to the transport protocol specified within the packet. If the system is configured as a router, datagrams that have not reached their final destination are sent to ip_forward for routing toward their final destination. Packets have a limited lifetime. If the TTL field drops to 0, the packet is dropped by ip_forward.

The Internet checksum function is used by many of the Internet protocols and implemented by in_cksum in Net/3. The IP checksum covers only the header (and options), not the data, which must be protected by checksums at the transport protocol level. As one of the most time-consuming operations in IP, the checksum function is often optimized for each platform.

Exercises

8.1 Should IP accept broadcast packets when there are no IP addresses assigned to any interfaces?

8.2 Modify ip_forward and ip_output to do an incremental update of the IP checksum when a packet without options is being forwarded.

8.3 Why is it necessary to check for a link-level broadcast (M_BCAST flag in an mbuf) and for an IP-level broadcast (in_canforward) when rejecting packets for forwarding? When would a packet arrive as a link-level broadcast but with an IP unicast destination?

8.4 Why isn't an error message returned to the sender when an IP packet arrives with checksum errors?

8.5 Assume that a process on a multihomed host has selected an explicit source address for its outgoing packets. Furthermore, assume that the packet's destination is reached through an interface other than the one selected as the packet's source address. What happens when the first-hop router discovers that the packets should be going through a different router? Is a redirect message sent to the host?

8.6 A new host is attached to a subnetted network and is configured to perform routing (`ipforwarding` equals 1) but its network interface has not been assigned a subnet mask. What happens when this host receives a subnet broadcast packet?

8.7 Why is it necessary to decrement `ip_ttl` after testing it (versus before) in Figure 8.17?

8.8 What would happen if two routers each considered the other the best next-hop destination for a packet?

8.9 Which addresses would not be checked in Figure 8.14 for a packet arriving at the SLIP interface? Would any additional addresses be checked that aren't listed in Figure 8.14?

8.10 `ip_forward` converts the fragment id from host byte order to network byte order before calling `icmp_error`. Why does it not also convert the fragment offset?

9

IP Option Processing

9.1 Introduction

Recall from Chapter 8 that the IP input function (`ipintr`) processes options after it verifies the packet's format (checksum, length, etc.) and before it determines whether the packet has reached its final destination. This implies that a packet's options are processed by every router it encounters and by the final destination host.

RFCs 791 and 1122 specify the IP options and processing rules. This chapter describes the format and processing of most IP options. We'll also show how a transport protocol can specify the IP options to be included in an IP datagram.

An IP packet can include optional fields that are processed before the packet is forwarded or accepted by a system. An IP implementation can handle options in any order; for Net/3, it is the order in which the options appear in the packet. Figure 9.1 shows that up to 40 bytes of options may follow the standard IP header.

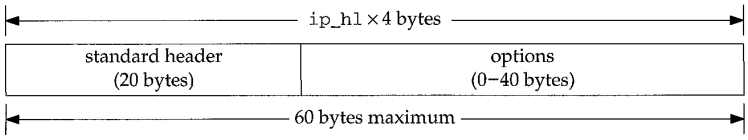


Figure 9.1 An IP header may contain 0 to 40 bytes of IP options.

9.2 Code Introduction

Two headers describe the data structures for IP options. Option processing code is found in two C files. Figure 9.2 lists the relevant files.

File	Description
`netinet/ip.h`	`ip_timestamp` structure
`netinet/ip_var.h`	`ipoption` structure
`netinet/ip_input.c`	option processing
`netinet/ip_output.c`	`ip_insertoptions` function

Figure 9.2 Files discussed in this chapter.

Global Variables

The two global variables described in Figure 9.3 support the reversal of source routes.

Variable	Datatype	Description
`ip_nhops`	`int`	hop count for previous source route
`ip_srcrt`	`struct ip_srcrt`	previous source route

Figure 9.3 Global variables introduced in this chapter.

Statistics

The only statistic updated by the options processing code is `ips_badoptions` from the `ipstat` structure, which Figure 8.4 described.

9.3 Option Format

The IP option field may contain 0 or more individual options. The two types of options, single-byte and multibyte, are illustrated in Figure 9.4.

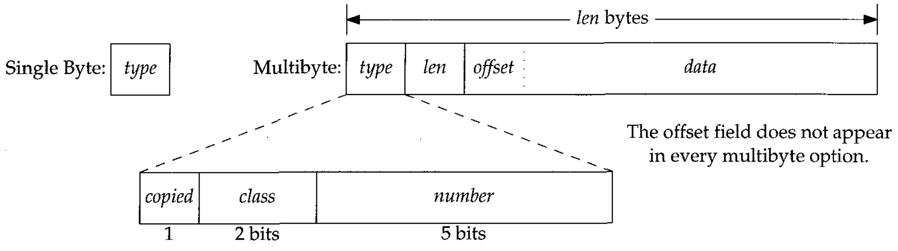


Figure 9.4 The organization of single-byte and multibyte IP options.

All options start with a 1-byte *type* field. In multibyte options, the *type* field is followed immediately by a *len* field, and the remaining bytes are the *data*. The first byte of the *data* field for many options is a 1-byte *offset* field, which points to a byte within the *data* field. The *len* byte covers the *type*, *len*, and *data* fields in its count. The *type* is further divided into three internal fields: a 1-bit *copied* flag, a 2-bit *class* field, and a 5-bit *number* field. Figure 9.5 lists the currently defined IP options. The first two options are single-byte options; the remainder are multibyte options.

Constant	Type		Length	Net/3	Description
	Decimal	Binary	(bytes)		
IPOPT_EOL	0–0–0 0	0–00–00000	1	•	end of option list (EOL)
IPOPT_NOP	0–0–1 1	0–00–00001	1	•	no operation (NOP)
IPOPT_RR	0–0–7 7	0–00–00111	varies	•	record route
IPOPT_TS	0–2–4 68	0–10–00100	varies	•	timestamp
IPOPT_SECURITY	1–0–2 130	1–00–00010	11		basic security
IPOPT_LSRR	1–0–3 131	1–00–00011	varies	•	loose source and record route (LSRR)
	1–0–5 133	1–00–00101	varies		extended security
IPOPT_SATID	1–0–8 136	1–00–01000	4		stream identifier
IPOPT_SSRR	1–0–9 137	1–00–01001	varies	•	strict source and record route (SSRR)

Figure 9.5 IP options defined by RFC 791.

The first column shows the Net/3 constant for the option, followed by the decimal and binary values of the type in columns 2 and 3, and the expected length of the option in column 4. The Net/3 column shows those options that are implemented in Net/3 by ip_dooptions. IP must silently ignore any option it does not understand. We don't describe the options that are not implemented in Net/3: security and stream ID. The stream ID option is obsolete and the security options are used primarily by the U.S. military. See RFC 791 for more information.

Net/3 examines the *copied* flag when it fragments a packet with options (Section 10.4). The flag indicates whether the individual option should be copied into the IP header of the fragments. The *class* field groups related options as described in Figure 9.6. All the options in Figure 9.5 have a *class* of 0 except for the timestamp option, which has a *class* of 2.

class	Description
0	control
1	reserved
2	debugging and measurement
3	reserved

Figure 9.6 The *class* field within an IP option.

9.4 ip_dooptions Function

In Figure 8.13 we saw that ipintr calls ip_dooptions just before it checks the destination address of the packet. ip_dooptions is passed a pointer, m, to a packet and processes the options it knows about. If ip_dooptions forwards the packet, as can happen with the LSRR and SSRR options, or discards the packet because of an error, it returns 1. If it doesn't forward the packet, ip_dooptions returns 0 and ipintr continues processing the packet.

ip_dooptions is a long function, so we show it in parts. The first part initializes a for loop to process each option in the header.

When processing an individual option, cp points to the first byte of the option. Figure 9.7 illustrates how the *type*, *length*, and, when applicable, the *offset* fields are accessed with constant offsets from cp.

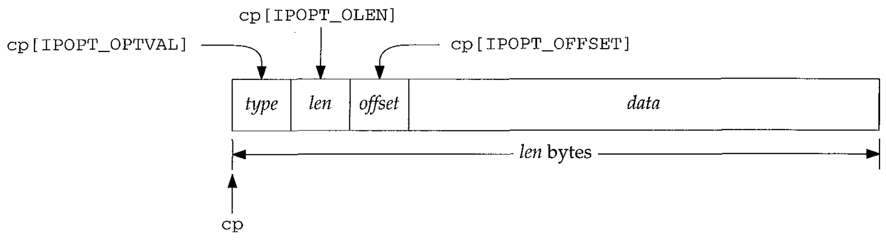


Figure 9.7 Access to IP option fields is by constant offsets.

The RFCs refer to the *offset* field as a *pointer*, which is slightly more descriptive than the term *offset*. The value of *offset* is the index (starting with *type* at index 1) of a byte within the option, and not a 0-based offset from *type*. The minimum value for *offset* is 4 (IPOPT_MINOFF), which points to the first byte of the *data* field in a multibyte option.

Figure 9.8 shows the overall organization of the ip_dooptions function.

553–566 ip_dooptions initializes the ICMP error type, type, to ICMP_PARAMPROB, which is a generic value for any error that does not have a specific error type of its own. For ICMP_PARAMPROB, code is the offset within the packet of the erroneous byte. This is the default ICMP error message; some options change these values.

ip points to an ip structure with a size of 20 bytes, so ip + 1 points to the next ip structure following the IP header. Since ip_dooptions wants the address of the *byte* after the IP header, the cast converts the resulting pointer to a pointer to an unsigned byte (u_char). Therefore cp points to the first byte beyond the standard IP header, which is the first byte of the IP options.

EOL and NOP processing

567–582 The for loop processes each option in the order it appears in the packet. An EOL option terminates the loop, as does an invalid option length (i.e., the option length indicates that the option data extends beyond the IP header). A NOP option is skipped when it appears. The default case for the switch statement implements the requirement that a system ignore unknown options.

The following sections describe each of the options handled within the switch statement. If ip_dooptions processes all the options in the packet without finding an error, control falls through to the code after the switch.

Source route forwarding

719–724 If the packet needs to be forwarded, forward is set by the SSRR or LSRR option processing code. The packet is passed to ip_forward with a 1 as the second argument to specify that the packet is source routed.

ip_input.c

```
int
ip_dooptions(m)
struct mbuf *m;
{
    struct ip *ip = mtod(m, struct ip *);
    u_char *cp;
    struct ip_timestamp *ipt;
    struct in_ifaddr *ia;
    int     opt, optlen, cnt, off, code, type = ICMP_PARAMPROB, forward = 0;
    struct in_addr *sin, dst;
    n_time  ntime;

    dst = ip->ip_dst;
    cp = (u_char *) (ip + 1);
    cnt = (ip->ip_hl << 2) - sizeof(struct ip);
    for (; cnt > 0; cnt -= optlen, cp += optlen) {
        opt = cp[IPOPT_OPTVAL];
        if (opt == IPOPT_EOL)
            break;
        if (opt == IPOPT_NOP)
            optlen = 1;
        else {
            optlen = cp[IPOPT_OLEN];
            if (optlen <= 0 || optlen > cnt) {
                code = &cp[IPOPT_OLEN] - (u_char *) ip;
                goto bad;
            }
        }
        switch (opt) {

        default:
            break;


                                    /* option processing */


    }
    if (forward) {
        ip_forward(m, 1);
        return (1);
    }
    return (0);

  bad:
    ip->ip_len -= ip->ip_hl << 2;   /* XXX icmp_error adds in hdr length */
    icmp_error(m, type, code, 0, 0);
    ipstat.ips_badoptions++;
    return (1);
}
```

ip_input.c

Figure 9.8 ip_dooptions function.

Recall from Section 8.5 that ICMP redirects are not generated for source-routed packets—this is the reason for the second argument to ip_forward.

ip_dooptions returns 1 if the packet has been forwarded. If the packet does not include a source route, 0 is returned to ipintr to indicate that the datagram needs further processing. Note that source route forwarding occurs whether the system is configured as a router (ipforwarding equals 1) or not.

This is a somewhat controversial policy, but is mandated by RFC 1122. RFC 1127 [Braden 1989c] describes this as an open issue.

Error handling

725–730 If an error occurs within the switch, ip_dooptions jumps to bad. The IP header length is subtracted from the packet length since icmp_error assumes the header length is not included in the packet length. icmp_error sends the appropriate error message, and ip_dooptions returns 1 to prevent ipintr from processing the discarded packet.

The following sections describe each of the options that are processed by Net/3.

9.5 Record Route Option

The record route option causes the route taken by a packet to be recorded within the packet as it traverses an internet. The size of the option is fixed by the source host when it constructs the option and must be large enough to hold all the expected addresses. Recall that only 40 bytes of options may appear in an IP packet. The record route option has 3 bytes of overhead followed by a list of addresses (4 bytes each). If it is the only option, up to 9 ($3 + 4 \times 9 = 39$) addresses may appear. Once the allocated space in the option has been filled, the packet is forwarded as usual but no more addresses are recorded by the intermediate systems.

Figure 9.9 illustrates the format of a record route option and Figure 9.10 shows the source code.

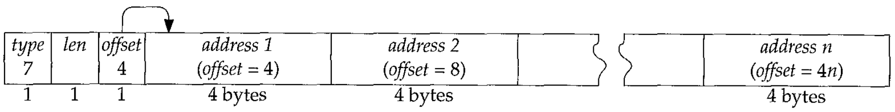


Figure 9.9 The record route option. n must be ≤ 9.

647–657 If the option offset is too small, ip_dooptions sends an ICMP parameter problem error. The variable code is set to the byte offset of the invalid option offset within the packet, and the ICMP parameter problem error has this code value when the error is generated at the label bad (Figure 9.8). If there is no space in the option for additional addresses, the option is ignored and processing continues with the next option.

Record address

658–673 If ip_dst is one of the systems addresses (the packet has arrived at its destination), the address of the receiving interface is recorded in the option; otherwise the address of

ip_input.c

```
        case IPOPT_RR:
            if ((off = cp[IPOPT_OFFSET]) < IPOPT_MINOFF) {
                code = &cp[IPOPT_OFFSET] - (u_char *) ip;
                goto bad;
            }
            /*
             * If no space remains, ignore.
             */
            off--;              /* 0 origin */
            if (off > optlen - sizeof(struct in_addr))
                        break;
            bcopy((caddr_t) (&ip->ip_dst), (caddr_t) & ipaddr.sin_addr,
                  sizeof(ipaddr.sin_addr));
            /*
             * locate outgoing interface; if we're the destination,
             * use the incoming interface (should be same).
             */
            if ((ia = (INA) ifa_ifwithaddr((SA) & ipaddr)) == 0 &&
                (ia = ip_rtaddr(ipaddr.sin_addr)) == 0) {
                type = ICMP_UNREACH;
                code = ICMP_UNREACH_HOST;
                goto bad;
            }
            bcopy((caddr_t) & (IA_SIN(ia)->sin_addr),
                  (caddr_t) (cp + off), sizeof(struct in_addr));
            cp[IPOPT_OFFSET] += sizeof(struct in_addr);
            break;
```

ip_input.c

Figure 9.10 `ip_dooptions` function: record route option processing.

the outgoing interface as provided by `ip_rtaddr` is recorded. The offset is updated to point to the next available address position in the option. If `ip_rtaddr` can't find a route to the destination, an ICMP host unreachable error is sent.

Section 7.3 of Volume 1 contains examples of the record route option.

`ip_rtaddr` Function

The `ip_rtaddr` function consults a route cache and, if necessary, the complete routing tables to locate a route to a given IP address. It returns a pointer to the `in_ifaddr` structure associated with the outgoing interface for the route. The function is shown in Figure 9.11.

Check IP forwarding cache

735–741 If the route cache is empty, or if `dest`, the only argument to `ip_rtaddr`, does not match the destination in the route cache, the routing tables must be consulted to select an outgoing interface.

ip_input.c
```
735 struct in_ifaddr *
736 ip_rtaddr(dst)
737 struct in_addr dst;
738 {
739     struct sockaddr_in *sin;

740     sin = (struct sockaddr_in *) &ipforward_rt.ro_dst;

741     if (ipforward_rt.ro_rt == 0 || dst.s_addr != sin->sin_addr.s_addr) {
742         if (ipforward_rt.ro_rt) {
743             RTFREE(ipforward_rt.ro_rt);
744             ipforward_rt.ro_rt = 0;
745         }
746         sin->sin_family = AF_INET;
747         sin->sin_len = sizeof(*sin);
748         sin->sin_addr = dst;

749         rtalloc(&ipforward_rt);
750     }
751     if (ipforward_rt.ro_rt == 0)
752         return ((struct in_ifaddr *) 0);
753     return ((struct in_ifaddr *) ipforward_rt.ro_rt->rt_ifa);
754 }
```
ip_input.c

Figure 9.11 ip_rtaddr function: locate outgoing interface.

Locate route

742–750 The old route (if any) is discarded and the new destination address is stored in *sin (which is the ro_dst member of the forwarding cache). rtalloc searches the routing tables for a route to the destination.

Return route information

751–754 If no route is available, a null pointer is returned. Otherwise, a pointer to the interface address structure associated with the selected route is returned.

9.6 Source and Record Route Options

Normally a packet is forwarded along a path chosen by the intermediate routers. The source and record route options allow the source host to specify an explicit path to the destination that overrides routing decisions of the intermediate routers. Furthermore, the route is recorded as the packet travels toward its destination.

A *strict* route includes the address of every intermediate router between the source and destination; a *loose* route specifies only some of the intermediate routers. Routers are free to choose any path between two systems listed in a loose route, whereas no intermediate routers are allowed between the systems listed in a strict route. We'll use Figure 9.12 to illustrate source route processing.

A, B, and C are routers and HS and HD are the source and destination hosts. Since each interface has its own IP address, we see that router A has three addresses: A_1, A_2,

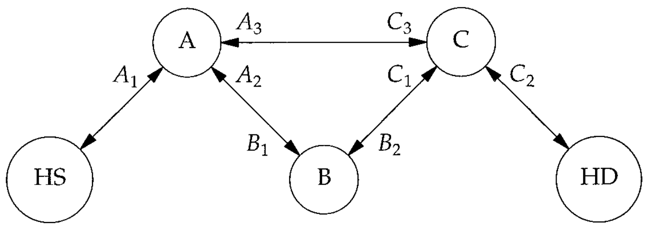


Figure 9.12 Source route example.

and A_3. Similarly, routers B and C have multiple addresses. Figure 9.13 shows the format of the source and record route options.

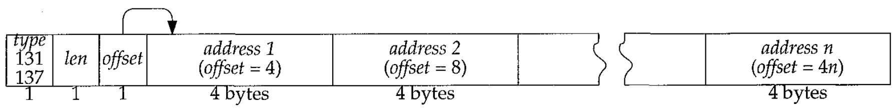

type 131 137
len
offset
address 1 (*offset* = 4)
address 2 (*offset* = 8)
address n (*offset* = 4*n*)
1
1
1
4 bytes
4 bytes
4 bytes

Figure 9.13 The loose and strict source routing options.

The source and destination addresses in the IP header and the offset and address list in the option specify the route and the packet's current location within the route. Figure 9.14 shows how this information changes as the packet follows the loose source route from HS to A to B to C to HD. The loose source route specified by the process are the four IP addresses: A_3, B_1, C_1, and HD. Each row represents the state of the packet when *sent* by the system shown in the first column. The last line shows the packet as received by HD. Figure 9.15 shows the relevant code.

System	IP Header		Source Route Option	
	`ip_src`	`ip_dst`	*offset*	addresses
HS	HS	A_3	4	• B_1 C_1 HD
A	HS	B_1	8	A_2 • C_1 HD
B	HS	C_1	12	A_2 B_2 • HD
C	HS	HD	16	A_2 B_2 C_2 •
HD	HS	HD	16	A_2 B_2 C_2 •

Figure 9.14 The source route option is modified as a packet traverses the route.

The • marks the position of *offset* relative to the addresses within the route. Notice that the address of the outgoing interface is placed in the option by each system. In particular, the original route specified A_3 as the first-hop destination but the output interface, A_2, was recorded in the route. In this way, the route taken by the packet is recorded in the option. This recorded route should be reversed by the destination system and attached to any reply packets so that they follow the same path as the initial packet but in the reverse direction.

Except for UDP, Net/3 reverses a received source route when responding.

ip_input.c

```
            /*
             * Source routing with record.
             * Find interface with current destination address.
             * If none on this machine then drop if strictly routed,
             * or do nothing if loosely routed.
             * Record interface address and bring up next address
             * component.  If strictly routed make sure next
             * address is on directly accessible net.
             */
        case IPOPT_LSRR:
        case IPOPT_SSRR:
            if ((off = cp[IPOPT_OFFSET]) < IPOPT_MINOFF) {
                code = &cp[IPOPT_OFFSET] - (u_char *) ip;
                goto bad;
            }
            ipaddr.sin_addr = ip->ip_dst;
            ia = (struct in_ifaddr *)
                ifa_ifwithaddr((struct sockaddr *) &ipaddr);
            if (ia == 0) {
                if (opt == IPOPT_SSRR) {
                    type = ICMP_UNREACH;
                    code = ICMP_UNREACH_SRCFAIL;
                    goto bad;
                }
                /*
                 * Loose routing, and not at next destination
                 * yet; nothing to do except forward.
                 */
                break;
            }
            off--;              /* 0 origin */
            if (off > optlen - sizeof(struct in_addr)) {
                /*
                 * End of source route.  Should be for us.
                 */
                save_rte(cp, ip->ip_src);
                break;
            }
            /*
             * locate outgoing interface
             */
            bcopy((caddr_t) (cp + off), (caddr_t) & ipaddr.sin_addr,
                  sizeof(ipaddr.sin_addr));
            if (opt == IPOPT_SSRR) {
#define INA struct in_ifaddr *
#define SA  struct sockaddr *
                if ((ia = (INA) ifa_ifwithdstaddr((SA) & ipaddr)) == 0)
                    ia = (INA) ifa_ifwithnet((SA) & ipaddr);
            } else
                ia = ip_rtaddr(ipaddr.sin_addr);
            if (ia == 0) {
                type = ICMP_UNREACH;
                code = ICMP_UNREACH_SRCFAIL;
636                 goto bad;
637             }
638             ip->ip_dst = ipaddr.sin_addr;
639             bcopy((caddr_t) & (IA_SIN(ia)->sin_addr),
640                   (caddr_t) (cp + off), sizeof(struct in_addr));
641             cp[IPOPT_OFFSET] += sizeof(struct in_addr);
642             /*
643              * Let ip_intr's mcast routing check handle mcast pkts
644              */
645             forward = !IN_MULTICAST(ntohl(ip->ip_dst.s_addr));
646             break;
```
ip_input.c

Figure 9.15 ip_dooptions function: LSRR and SSRR option processing.

583–612 Net/3 sends an ICMP parameter problem error with the appropriate value of code if the option offset is smaller than 4 (IPOPT_MINOFF). If the destination address of the packet does not match one of the local addresses and the option is a strict source route (IPOPT_SSRR), an ICMP source route failure error is sent. If a local address isn't listed in the route, the previous system sent the packet to the wrong host. This isn't an error for a loose source route (IPOPT_LSRR); it means IP must forward the packet toward the destination.

End of source route

613–620 Decrementing off converts it to a byte offset from the start of the option. If ip_dst in the IP header is one of the local addresses and off points beyond the end of the source route, there are no more addresses in the source route and the packet has reached its final destination. save_rte makes a copy of the route in the static structure ip_srcrt and saves the number of addresses in the route in the global ip_nhops (Figure 9.18).

> ip_srcrt is declared as an external static structure since it is only accessed by the functions declared in ip_input.c.

Update packet for next hop

621–637 If ip_dst is one of the local addresses and offset points to an address within the option, this system is an intermediate system specified in the source route and the packet has not reached its final destination. During strict routing, the next system must be on a directly connected network. ifa_ifwithdst and ifa_ifwithnet locate a route to the next system by searching the configured interfaces for a matching destination address (a point-to-point interface) or a matching network address (a broadcast interface). During loose routing, ip_rtaddr (Figure 9.11) locates the route to the next system by querying the routing tables. If no interface or route is found for the next system, an ICMP source route failure error is sent.

638–644 If an interface or a route is located, ip_dooptions sets ip_dst to the IP address pointed to by off. Within the source route option, the intermediate address is replaced with the address of the outgoing interface, and the offset is incremented to point to the next address in the route.

Multicast destinations

645–646 If the new destination address is not a multicast address, setting `forward` to 1 indicates that the packet should be forwarded after `ip_dooptions` processes all the options instead of returning the packet to `ipintr`.

Multicast addresses within a source route enable two multicast routers to communicate through intermediate routers that don't support multicasting. Chapter 14 describes this technique in more detail.

Section 8.5 of Volume 1 contains more examples of the source route options.

`save_rte` Function

RFC 1122 requires that the route recorded in a packet be made available to the transport protocol at the final destination. The transport protocols must reverse the route and attach it to any reply packets. The function `save_rte`, shown in Figure 9.18, saves source routes in an `ip_srcrt` structure, shown in Figure 9.16

ip_input.c

```
57 int     ip_nhops = 0;
58 static struct ip_srcrt {
59     struct in_addr dst;         /* final destination */
60     char    nop;                /* one NOP to align */
61     char    srcopt[IPOPT_OFFSET + 1];   /* OPTVAL, OLEN and OFFSET */
62     struct in_addr route[MAX_IPOPTLEN / sizeof(struct in_addr)];
63 } ip_srcrt;
```

ip_input.c

Figure 9.16 `ip_srcrt` structure.

The declaration of `route` is incorrect, though the error is benign. It should be

```
struct in_addr route[(MAX_IPOPTLEN - 3)/ sizeof(struct in_addr)];
```

The discussion with Figures 9.26 and 9.27 covers this in more detail.

57–63 This code defines the `ip_srcrt` structure and declares the static variable `ip_srcrt`. Only two functions access `ip_srcrt`: `save_rte`, which copies the source route from an incoming packet into `ip_srcrt`; and `ip_srcroute`, which creates a reversed route route from `ip_srcrt`. Figure 9.17 illustrates source route processing.

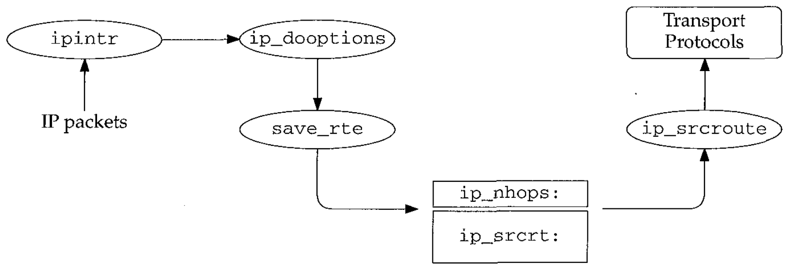


Figure 9.17 Processing of reversed source routes.

ip_input.c
```
759 void
760 save_rte(option, dst)
761 u_char *option;
762 struct in_addr dst;
763 {
764     unsigned olen;

765     olen = option[IPOPT_OLEN];
766     if (olen > sizeof(ip_srcrt) - (1 + sizeof(dst)))
767         return;
768     bcopy((caddr_t) option, (caddr_t) ip_srcrt.srcopt, olen);
769     ip_nhops = (olen - IPOPT_OFFSET - 1) / sizeof(struct in_addr);
770     ip_srcrt.dst = dst;
771 }
```
ip_input.c

Figure 9.18 save_rte function.

759–771 ip_dooptions calls save_rte when a source routed packet has reached its final destination. option is a pointer to a packet's source route option, and dst is ip_src from the packet's header (i.e., the destination of the return route, HS from Figure 9.12). If the option length is larger than the ip_srcrt structure, save_rte returns immediately.

This would never happen, as the ip_srcrt structure is larger than the largest option length (40 bytes).

save_rte copies the option into ip_srcrt, computes and saves the number of hops in the source route in ip_nhops, and saves the destination of the return route in dst.

ip_srcroute Function

When responding to a packet, ICMP and the standard transport protocols must reverse any source route that the packet carried. The reversed source route is constructed from the saved route by ip_srcroute, which is shown in Figure 9.19.

777–783 ip_srcroute reverses the route saved in the ip_srcrt structure and returns the result formatted as an ipoption structure (Figure 9.26). If ip_nhops is 0, there is no saved route, so ip_srcroute returns a null pointer.

Recall that in Figure 8.13, ipintr cleared ip_nhops when a valid packet arrives. The transport protocols must call ip_srcroute and save the reversed route themselves before the next packet arrives. As noted earlier, this is OK since the transport layer (TCP or UDP) is called by ipintr for each packet, before the next packet on IP's input queue is processed.

Allocate mbuf for source route

784–786 If ip_nhops is nonzero, ip_srcroute allocates an mbuf and sets m_len large enough to include the first-hop destination, the option header information (OPTSIZ), and the reversed route. If the allocation fails, a null pointer is returned as if there were no source route available.

ip_input.c

```
struct mbuf *
ip_srcroute()
{
    struct in_addr *p, *q;
    struct mbuf *m;

    if (ip_nhops == 0)
        return ((struct mbuf *) 0);
    m = m_get(M_DONTWAIT, MT_SOOPTS);
    if (m == 0)
        return ((struct mbuf *) 0);

#define OPTSIZ  (sizeof(ip_srcrt.nop) + sizeof(ip_srcrt.srcopt))

    /* length is (nhops+1)*sizeof(addr) + sizeof(nop + srcrt header) */
    m->m_len = ip_nhops * sizeof(struct in_addr) + sizeof(struct in_addr) +
            OPTSIZ;

    /*
     * First save first hop for return route
     */
    p = &ip_srcrt.route[ip_nhops - 1];
    *(mtod(m, struct in_addr *)) = *p--;

    /*
     * Copy option fields and padding (nop) to mbuf.
     */
    ip_srcrt.nop = IPOPT_NOP;
    ip_srcrt.srcopt[IPOPT_OFFSET] = IPOPT_MINOFF;
    bcopy((caddr_t) & ip_srcrt.nop,
          mtod(m, caddr_t) + sizeof(struct in_addr), OPTSIZ);
    q = (struct in_addr *) (mtod(m, caddr_t) +
                            sizeof(struct in_addr) + OPTSIZ);
#undef OPTSIZ
    /*
     * Record return path as an IP source route,
     * reversing the path (pointers are now aligned).
     */
    while (p >= ip_srcrt.route) {
        *q++ = *p--;
    }
    /*
     * Last hop goes to final destination.
     */
    *q = ip_srcrt.dst;
    return (m);
}
```

ip_input.c

Figure 9.19 ip_srcroute function.

p is initialized to point to the end of the incoming route, and ip_srcroute copies the last recorded address to the front of the mbuf where it becomes the outgoing first-hop destination for the reversed route. Then the function copies a NOP option (Exercise 9.4) and the source route information into the mbuf.

805–818 The `while` loop copies the remaining IP addresses from the source route into the mbuf in reverse order. The last address in the route is set to the source address from the incoming packet, which `save_rte` placed in `ip_srcrt.dst`. A pointer to the mbuf is returned. Figure 9.20 illustrates the construction of the reversed route with the route from Figure 9.12.

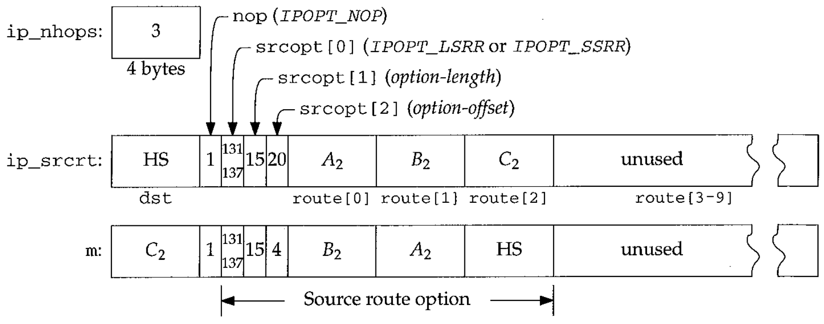


Figure 9.20 `ip_srcroute` reverses the route in `ip_srcrt`.

9.7 Timestamp Option

The timestamp option causes each system to record its notion of the current time within the option as the packet traverses an internet. The time is expected to be in milliseconds since midnight UTC, and is recorded in a 32-bit field.

If the system does not keep accurate UTC (within a few minutes) or the time is not updated at least 15 times per second, it is not considered a standard time. A nonstandard time must have the high-order bit of the timestamp field set.

There are three types of timestamp options, which Net/3 accesses through the `ip_timestamp` structure shown in Figure 9.22.

114–133 As in the `ip` structure (Figure 8.10), `#ifs` ensure that the bit fields access the correct bits in the option. Figure 9.21 lists the three types of timestamp options specified by `ipt_flg`.

ipt_flg	Value	Description
IPOPT_TS_TSONLY	0	record timestamps
IPOPT_TS_TSANDADDR	1	record addresses and timestamps
	2	reserved
IPOPT_TS_PRESPEC	3	record timestamps only at the prespecified systems
	4–15	reserved

Figure 9.21 Possible values for `ipt_flg`.

The originating host must construct the timestamp option with a data area large enough to hold all expected timestamps and addresses. For a timestamp option with an

ip.h
```
struct ip_timestamp {
    u_char  ipt_code;           /* IPOPT_TS */
    u_char  ipt_len;            /* size of structure (variable) */
    u_char  ipt_ptr;            /* index of current entry */
#if BYTE_ORDER == LITTLE_ENDIAN
    u_char  ipt_flg:4,          /* flags, see below */
            ipt_oflw:4;         /* overflow counter */
#endif
#if BYTE_ORDER == BIG_ENDIAN
    u_char  ipt_oflw:4,         /* overflow counter */
            ipt_flg:4;          /* flags, see below */
#endif
    union ipt_timestamp {
        n_long  ipt_time[1];
        struct ipt_ta {
            struct in_addr ipt_addr;
            n_long  ipt_time;
        } ipt_ta[1];
    } ipt_timestamp;
};
```
ip.h

Figure 9.22 `ip_timestamp` structure and constants.

`ipt_flg` of 3, the originating host fills in the addresses of the systems at which a timestamp should be recorded when it constructs the option. Figure 9.23 shows the organization of the three timestamp options.

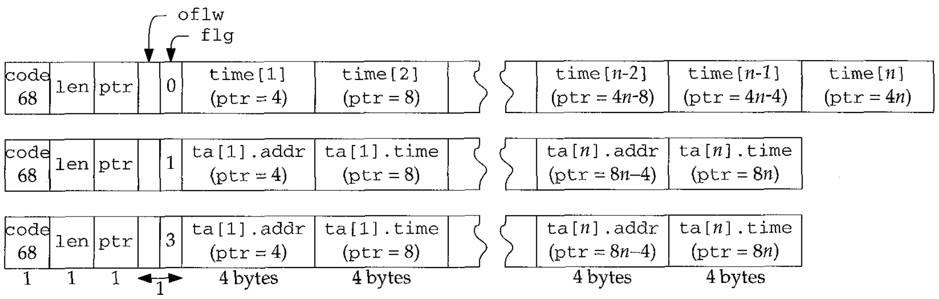


Figure 9.23 The three timestamp options (`ipt_` omitted).

Because only 40 bytes are available for IP options, the timestamp options are limited to nine timestamps (`ipt_flg` equals 0) or four pairs of addresses and timestamps (`ipt_flg` equals 1 or 3). Figure 9.24 shows the processing for the three different timestamp option types.

674–684 `ip_dooptions` sends an ICMP parameter problem error if the option length is less than 5 bytes (the minimum size of a timestamp option). The `oflw` field counts the number of systems unable to register timestamps because the data area of the option was full. `oflw` is incremented if the data area is full, and when it itself overflows at 16 (it is a 4-bit field), an ICMP parameter problem error is sent.

ip_input.c

```
    case IPOPT_TS:
        code = cp - (u_char *) ip;
        ipt = (struct ip_timestamp *) cp;
        if (ipt->ipt_len < 5)
            goto bad;
        if (ipt->ipt_ptr > ipt->ipt_len - sizeof(long)) {
            if (++ipt->ipt_oflw == 0)
                goto bad;
            break;
        }
        sin = (struct in_addr *) (cp + ipt->ipt_ptr - 1);
        switch (ipt->ipt_flg) {

        case IPOPT_TS_TSONLY:
            break;

        case IPOPT_TS_TSANDADDR:
            if (ipt->ipt_ptr + sizeof(n_time) +
                sizeof(struct in_addr) > ipt->ipt_len)
                        goto bad;
            ipaddr.sin_addr = dst;
            ia = (INA) ifaof_ifpforaddr((SA) & ipaddr,
                                        m->m_pkthdr.rcvif);
            if (ia == 0)
                continue;
            bcopy((caddr_t) & IA_SIN(ia)->sin_addr,
                  (caddr_t) sin, sizeof(struct in_addr));
            ipt->ipt_ptr += sizeof(struct in_addr);
            break;

        case IPOPT_TS_PRESPEC:
            if (ipt->ipt_ptr + sizeof(n_time) +
                sizeof(struct in_addr) > ipt->ipt_len)
                        goto bad;
            bcopy((caddr_t) sin, (caddr_t) & ipaddr.sin_addr,
                  sizeof(struct in_addr));
            if (ifa_ifwithaddr((SA) & ipaddr) == 0)
                continue;
            ipt->ipt_ptr += sizeof(struct in_addr);
            break;

        default:
            goto bad;
        }
        ntime = iptime();
        bcopy((caddr_t) & ntime, (caddr_t) cp + ipt->ipt_ptr - 1,
              sizeof(n_time));
        ipt->ipt_ptr += sizeof(n_time);
    }
}
```

ip_input.c

Figure 9.24 ip_dooptions function: timestamp option processing.

Timestamp only

685–687 For a timestamp option with an `ipt_flg` of 0 (`IPOPT_TS_TSONLY`), all the work is done after the `switch`.

Timestamp and address

688–700 For a timestamp option with an `ipt_flg` of 1 (`IPOPT_TS_TSANDADDR`), the address of the receiving interface is recorded (if room remains in the data area), and the option pointer is advanced. Because Net/3 supports multiple IP addresses on a single interface, `ip_dooptions` calls `ifaof_ifpforaddr` to select the address that best matches the original destination address of the packet (i.e., the destination before any source routing has occurred). If there is no match, the timestamp option is skipped. (`INA` and `SA` were defined in Figure 9.15.)

Timestamp at prespecified addresses

701–710 If `ipt_flg` is 3 (`IPOPT_TS_PRESPEC`), `ifa_ifwithaddr` determines if the next address specified in the option matches one of the system's addresses. If not, this option requires no processing at this system; the `continue` forces `ip_dooptions` to proceed to the next option. If the next address matches one of the system's addresses, the option pointer is advanced to the next position and control continues after the `switch`.

Insert timestamp

711–713 Invalid `ipt_flg` values are caught at `default` where control jumps to `bad`.

714–719 The timestamps are placed in the option by the code that follows the `switch` statement. `iptime` returns the number of milliseconds since midnight UTC. `ip_dooptions` records the timestamp and increments the option offset to the next position.

`iptime` Function

Figure 9.25 shows the implementation of `iptime`.

ip_icmp.c

```
458 n_time
459 iptime()
460 {
461     struct timeval atv;
462     u_long  t;

463     microtime(&atv);
464     t = (atv.tv_sec % (24 * 60 * 60)) * 1000 + atv.tv_usec / 1000;
465     return (htonl(t));
466 }
```

ip_icmp.c

Figure 9.25 `iptime` function.

458–466 `microtime` returns the time since midnight January 1, 1970, UTC, in a `timeval` structure. The number of milliseconds since midnight is computed using `atv` and returned in network byte order.

Section 7.4 of Volume 1 provides several timestamp option examples.

9.8 ip_insertoptions Function

We saw in Section 8.6 that the ip_output function accepts a packet and options. When the function is called from ip_forward, the options are already part of the packet so ip_forward always passes a null option pointer to ip_output. The transport protocols, however, may pass options to ip_forward where they are merged with the packet by ip_insertoptions (called by ip_output in Figure 8.22).

ip_insertoptions expects the options to be formatted in an ipoption structure, shown in Figure 9.26.

```
                                                                          ip_var.h
92 struct ipoption {
93     struct in_addr ipopt_dst;    /* first-hop dst if source routed */
94     char    ipopt_list[MAX_IPOPTLEN];    /* options proper */
95 };
                                                                          ip_var.h
```

Figure 9.26 ipoption structure.

92–95 The structure has only two members: ipopt_dst, which contains the first-hop destination if the option list contains a source route, and ipopt_list, which is an array of at most 40 (MAX_IPOPTLEN) bytes of options formatted as we have described in this chapter. If the option list does not include a source route, ipopt_dst is all 0s.

Note that the ip_srcrt structure (Figure 9.16) and the mbuf returned by ip_srcroute (Figure 9.19) both conform to the format specified by the ipoption structure. Figure 9.27 compares the ip_srcrt and ipoption structures.

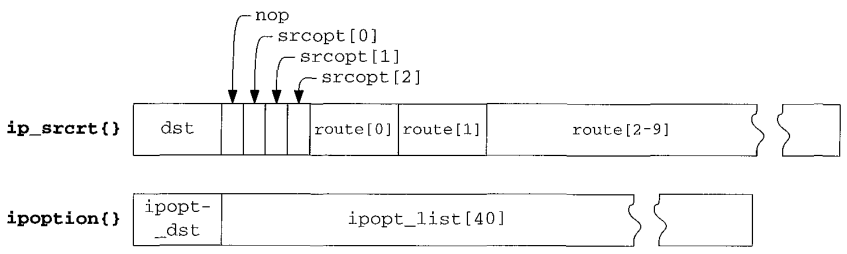


Figure 9.27 The ip_srcrt and ipoption structures.

The ip_srcrt structure is 4 bytes larger than the ipoption structure. The last entry in the route array (route[9]) is never filled because it would make the source route option 44 bytes long, larger than the IP header can accommodate (Figure 9.16).

The ip_insertoptions function is shown in Figure 9.28.

352–364 ip_insertoptions has three arguments: m, the outgoing packet; opt, the options formatted in an ipoption structure; and phlen, a pointer to an integer where the new header length (after options are inserted) is returned. If the size of packet with the options exceeds the maximum packet size of 65,535 (IP_MAXPACKET) bytes, the options are silently discarded. ip_dooptions does not expect ip_insertoptions ever to fail, so there is no way to report the error. Fortunately, few applications attempt to send a maximally sized datagram, let alone one with options.

ip_output.c

```
352 static struct mbuf *
353 ip_insertoptions(m, opt, phlen)
354 struct mbuf *m;
355 struct mbuf *opt;
356 int     *phlen;
357 {
358     struct ipoption *p = mtod(opt, struct ipoption *);
359     struct mbuf *n;
360     struct ip *ip = mtod(m, struct ip *);
361     unsigned optlen;

362     optlen = opt->m_len - sizeof(p->ipopt_dst);
363     if (optlen + (u_short) ip->ip_len > IP_MAXPACKET)
364         return (m);             /* XXX should fail */
365     if (p->ipopt_dst.s_addr)
366         ip->ip_dst = p->ipopt_dst;
367     if (m->m_flags & M_EXT || m->m_data - optlen < m->m_pktdat) {
368         MGETHDR(n, M_DONTWAIT, MT_HEADER);
369         if (n == 0)
370             return (m);
371         n->m_pkthdr.len = m->m_pkthdr.len + optlen;
372         m->m_len -= sizeof(struct ip);
373         m->m_data += sizeof(struct ip);
374         n->m_next = m;
375         m = n;
376         m->m_len = optlen + sizeof(struct ip);
377         m->m_data += max_linkhdr;
378         bcopy((caddr_t) ip, mtod(m, caddr_t), sizeof(struct ip));
379     } else {
380         m->m_data -= optlen;
381         m->m_len += optlen;
382         m->m_pkthdr.len += optlen;
383         ovbcopy((caddr_t) ip, mtod(m, caddr_t), sizeof(struct ip));
384     }
385     ip = mtod(m, struct ip *);
386     bcopy((caddr_t) p->ipopt_list, (caddr_t) (ip + 1), (unsigned) optlen);
387     *phlen = sizeof(struct ip) + optlen;
388     ip->ip_len += optlen;
389     return (m);
390 }
```

ip_output.c

Figure 9.28 `ip_insertoptions` function.

365–366 If `ipopt_dst.s_addr` specifies a nonzero address, then the options include a source route and `ip_dst` in the packet's header is replaced with the first-hop destination from the source route.

In Section 26.2 we'll see that TCP calls `MGETHDR` to allocate a separate mbuf for the IP and TCP headers. Figure 9.29 shows the mbuf organization for a TCP segment before the code in lines 367 to 378 is executed.

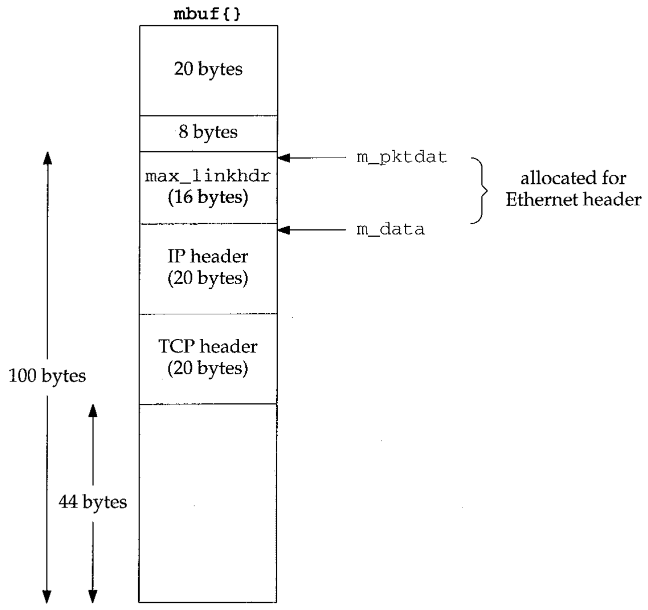


Figure 9.29 ip_insertoptions function: TCP segment.

If the options to be inserted occupy more than 16 bytes, the test on line 367 is true and MGETHDR is called to allocate an additional mbuf. Figure 9.30 shows the organization of the mbufs after the options have been copied into the new mbuf.

367–378 If the packet header is stored in a cluster, or the first mbuf does not have room for the options, ip_insertoptions allocates a new packet header mbuf, initializes its length, trims the IP header from the old mbuf, and moves the header from the old mbuf to the new mbuf.

As described in Section 23.6, UDP uses M_PREPEND to place the UDP and IP headers at the end of an mbuf, separate from the data. This is illustrated in Figure 9.31.

Because the headers are located at the end of the mbuf, there is always room for IP options in the mbuf and the condition on line 367 is always false for UDP.

379–384 If the packet has room at the beginning of the mbuf's data area for the options, m_data and m_len are adjusted to contain optlen more bytes, and the current IP header is moved by ovbcopy (which can handle overlapping source and destinations) to leave room for the options.

385–390 ip_insertoptions can now copy the ipopt_list member of the ipoption structure directly into the mbuf just after the IP header. ip_insertoptions stores the new header length in *phlen, adjusts the datagram length (ip_len), and returns a pointer to the packet header mbuf.

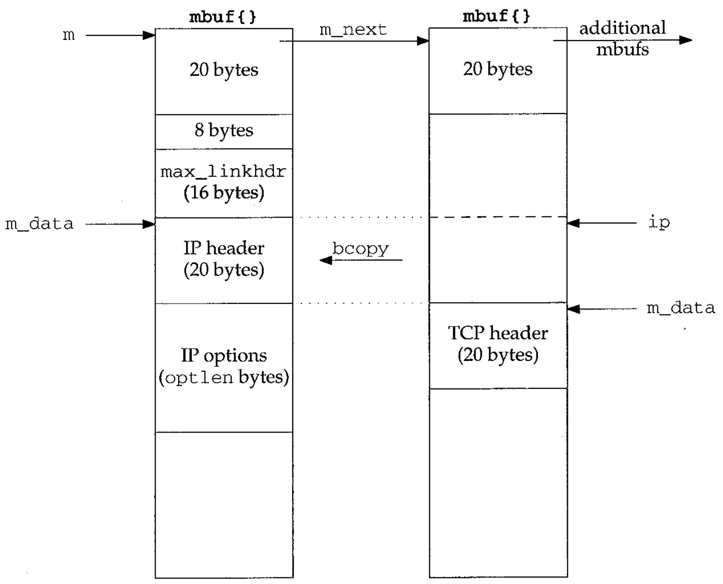


Figure 9.30 ip_insertoptions function: TCP segment, after options have been copied.

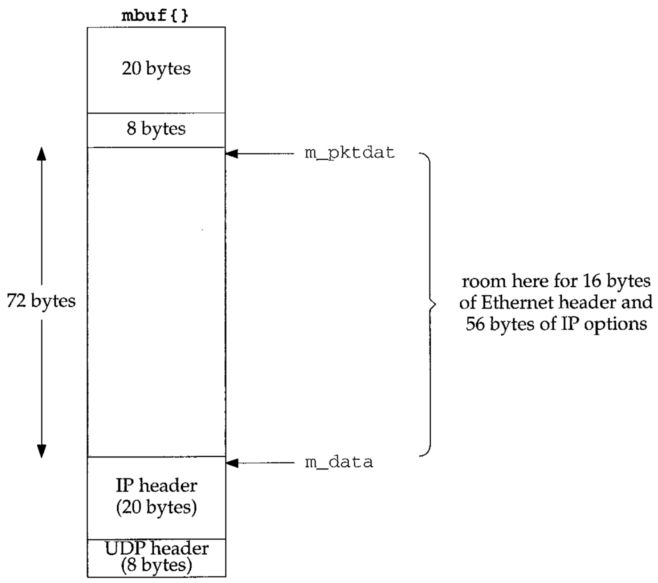


Figure 9.31 ip_insertoptions function: UDP datagram.

9.9 ip_pcbopts Function

The ip_pcbopts function converts the list of IP options provided with the IP_OPTIONS socket option into the form expected by ip_output: an ipoption structure.

ip_output.c

```
int
ip_pcbopts(pcbopt, m)
struct mbuf **pcbopt;
struct mbuf *m;
{
    cnt, optlen;
    u_char *cp;
    u_char  opt;

    /* turn off any old options */
    if (*pcbopt)
        (void) m_free(*pcbopt);
    *pcbopt = 0;
    if (m == (struct mbuf *) 0 || m->m_len == 0) {
        /*
         * Only turning off any previous options.
         */
        if (m)
            (void) m_free(m);
        return (0);
    }
    if (m->m_len % sizeof(long))
            goto bad;
    /*
     * IP first-hop destination address will be stored before
     * actual options; move other options back
     * and clear it when none present.
     */
    if (m->m_data + m->m_len + sizeof(struct in_addr) >= &m->m_dat[MLEN])
            goto bad;
    cnt = m->m_len;
    m->m_len += sizeof(struct in_addr);
    cp = mtod(m, u_char *) + sizeof(struct in_addr);
    ovbcopy(mtod(m, caddr_t), (caddr_t) cp, (unsigned) cnt);
    bzero(mtod(m, caddr_t), sizeof(struct in_addr));

    for (; cnt > 0; cnt -= optlen, cp += optlen) {
        opt = cp[IPOPT_OPTVAL];
        if (opt == IPOPT_EOL)
            break;
        if (opt == IPOPT_NOP)
            optlen = 1;
        else {
            optlen = cp[IPOPT_OLEN];
            if (optlen <= IPOPT_OLEN || optlen > cnt)
                goto bad;
        }
604         switch (opt) {

605         default:
606             break;

607         case IPOPT_LSRR:
608         case IPOPT_SSRR:
609             /*
610              * user process specifies route as:
611              *   ->A->B->C->D
612              * D must be our final destination (but we can't
613              * check that since we may not have connected yet).
614              * A is first hop destination, which doesn't appear in
615              * actual IP option, but is stored before the options.
616              */
617             if (optlen < IPOPT_MINOFF - 1 + sizeof(struct in_addr))
618                     goto bad;
619             m->m_len -= sizeof(struct in_addr);
620             cnt -= sizeof(struct in_addr);
621             optlen -= sizeof(struct in_addr);
622             cp[IPOPT_OLEN] = optlen;
623             /*
624              * Move first hop before start of options.
625              */
626             bcopy((caddr_t) & cp[IPOPT_OFFSET + 1], mtod(m, caddr_t),
627                   sizeof(struct in_addr));
628             /*
629              * Then copy rest of options back
630              * to close up the deleted entry.
631              */
632             ovbcopy((caddr_t) (&cp[IPOPT_OFFSET + 1] +
633                                sizeof(struct in_addr)),
634                             (caddr_t) & cp[IPOPT_OFFSET + 1],
635                             (unsigned) cnt + sizeof(struct in_addr));
636             break;
637         }
638     }
639     if (m->m_len > MAX_IPOPTLEN + sizeof(struct in_addr))
640             goto bad;
641     *pcbopt = m;
642     return (0);

643   bad:
644     (void) m_free(m);
645     return (EINVAL);
646 }
```
ip_output.c

Figure 9.32 ip_pcbopts function.

559–562 The first argument, pcbopt, references the pointer to the current list of options. The function replaces this pointer with a pointer to the new list of options constructed from options specified in the mbuf chain pointed to by the second argument, m. The option list prepared by the process to be included with the IP_OPTIONS socket option looks like a standard list of IP options except for the format of the LSRR and SSRR options. For these options, the first-hop destination is included as the first address in the route. Figure 9.14 shows that the first-hop destination appears as the destination address in the outgoing packet, not as the first address in the route.

Discard previous options

563–580 Any previous options are discarded by `m_free` and `*pcbopt` is cleared. If the process passed an empty mbuf or didn't pass an mbuf at all, the function returns immediately without installing any new options.

If the new list of options is not padded to a 4-byte boundary, `ip_pcbopts` jumps to `bad`, discards the list and returns `EINVAL`.

The remainder of the function rearranges the list to look like an `ipoption` structure. Figure 9.33 illustrates this process.

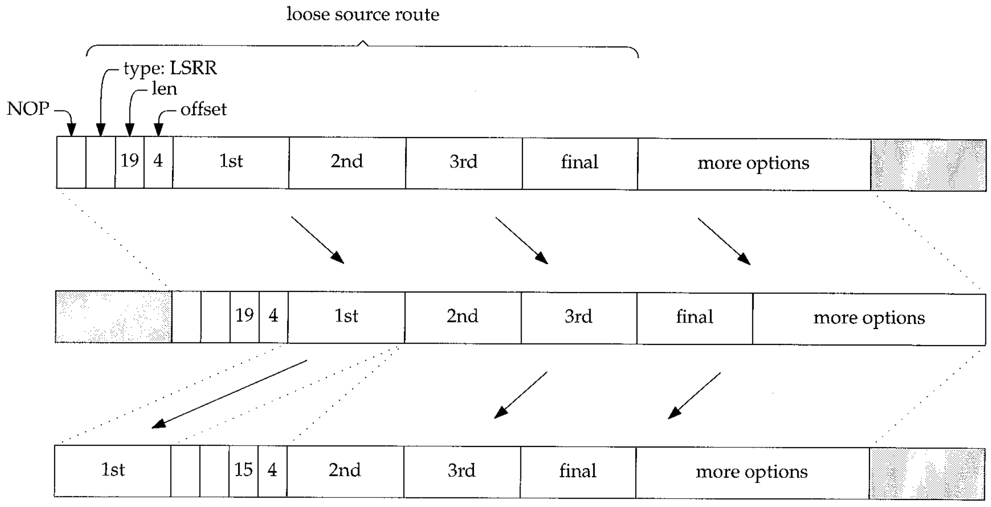


Figure 9.33 `ip_pcbopts` option list processing.

Make room for first-hop destination

581–592 If there is room in the mbuf, all the data is shifted by 4 bytes (the size of an `in_addr` structure) toward the end of the mbuf. `ovbcopy` performs the copy. `bzero` clears the 4 bytes at the start of the mbuf.

Scan option list

593–606 The `for` loop scans the option list looking for LSRR and SSRR options. For multibyte options, the loop also verifies that the length of the option is reasonable.

Rearrange LSRR or SRR option

607–638 When the loop locates a LSRR or SRR option, it decrements the mbuf size, the loop index, and the option length by 4, since the first address in the option will be removed and shifted to the front of the mbuf.

`bcopy` moves the first address and `ovbcopy` shifts the remainder of the options by 4 bytes to fill the gap left by the first address.

Cleanup

639–646 After the loop, the size of the option list (including the first-hop address) must be no more than 44 (MAX_IPOPTLEN + 4) bytes. A larger list does not fit in the IP packet header. The list is saved in *pcbopt and the function returns.

9.10 Limitations

Options are rarely present in IP datagrams other than those created by administrative and diagnostic tools. Volume 1 discusses two of the more common tools, ping and traceroute. It is difficult to write applications that utilize IP options. The programming interfaces are poorly documented and not well standardized. Most vendor supplied applications, such as Telnet and FTP, do not provide a way for a user to specify options such as a source route.

The usefulness of the record route, timestamp, and source route options in a large internet is limited by the maximum size of an IP header. Most routes contain more hops than can be represented in the 40 option bytes. When multiple options appear in the same packet, the available space is almost useless. IPv6 addresses this problem with a more flexible option header design.

During fragmentation, IP copies only some options into the noninitial fragments, since the options in noninitial fragments are discarded during reassembly. Only options from the initial fragment are made available to the transport protocol at the destination (Section 10.6). But some, such as source route, must be copied to each fragment, even if they are discarded in noninitial fragments at the destination.

9.11 Summary

In this chapter we showed the format and processing of IP options. We didn't cover the security and stream ID options since they are not implemented in Net/3.

We saw that the size of multibyte options is fixed by the source host when it constructs the option. The usefulness of IP options is severely limited by the small maximum option header size of 40 bytes.

The source route options require the most support. Incoming source routes are saved by save_rte and reversed by ip_srcroute. A host that does not normally forward packets may forward source routed packets, but RFC 1122 requires this capability to be disabled by default. Net/3 does not have a switch for this feature and always forwards source routed packets.

Finally, we saw how options are merged into an outgoing packet by ip_insertoptions.

Exercises

9.1 What would happen if a packet contained two different source route options?

9.2 Some commercial routers can be configured to discard packets based on their IP destination address. In this way, a machine or group of machines can be isolated from the larger internet beyond the router. Describe how source routed packets can bypass this mechanism. Assume that there is at least one host within the network that the router is not blocking, and that it forwards source routed datagrams.

9.3 Some hosts may not be configured with a default route. In general, this prevents communication with the host since the host can't route to destinations outside its directly connected networks. Describe how a source route can enable communication with this type of host.

9.4 Why is a NOP used in the `ip_srcrt` structure in Figure 9.16?

9.5 Can a nonstandard time value be confused with a standard time value in the timestamp options?

9.6 `ip_dooptions` saves the destination address of the packet in `dest` before processing any options (Figure 9.8). Why?