Programming Linux sockets, Part 1: Using TCP/IP

Creating an echo server and client

Skill Level: Introductory

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This introductory-level tutorial shows how to begin programming with sockets. Focusing on C and Python, it guides you through the creation of an echo server and client, which connect over TCP/IP. Fundamental network, layer, and protocol concepts are described, and sample source code abounds.

Section 1. Before you start

About this tutorial

IP sockets are the lowest-level layer upon which high level Internet protocols are built: everything from HTTP to SSL to POP3 to Kerberos to UDP-Time. To implement custom protocols, or to customize implementation of well-known protocols, a programmer needs a working knowledge of the basic socket infrastructure. While this tutorial focuses primarily on C programming, and also uses Python as a representative higher-level language for examples, a similar API is available in many languages.

This tutorial introduces you to the basics of programming custom network tools using the cross-platform Berkeley Sockets Interface. Almost all network tools in Linux and other UNIX-based operating systems rely on this interface.

Prerequisites

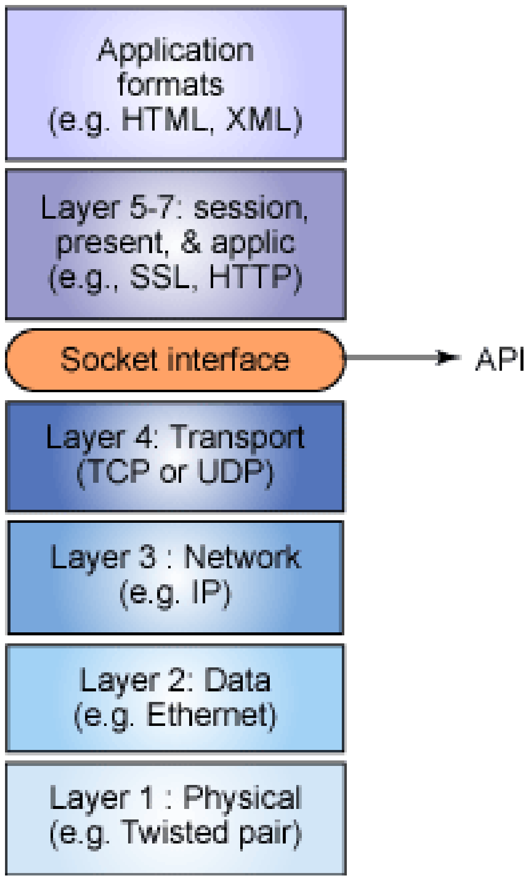
This tutorial requires a minimal level of knowledge of C, and ideally of Python also (mostly for the follow-on Part 2). However, if you are not familiar with either programming language, you should be able to make it through with a bit of extra effort; most of the underlying concepts will apply equally to other programming languages, and calls will be quite similar in most high-level scripting languages like Ruby, Perl, TCL, and so on.

Although this tutorial introduces the basic concepts behind IP (Internet Protocol) networks, some prior acquaintance with the concept of network protocols and layers will be helpful (see Resources at the end of this tutorial for background documents).

Section 2. Understanding IP networks and network layers

What is a network?

Figure 1. Network layers


Application formats (e.g. HTML, XML)
Layer 5-7: session, present, & applic (e.g., SSL, HTTP)
Socket interface
API
Layer 4: Transport (TCP or UDP)
Layer 3 : Network (e.g. IP)
Layer 2: Data (e.g. Ethernet)
Layer 1 : Physical (e.g. Twisted pair)

What we usually call a computer network is composed of a number of *network layers* (see Resources for a useful reference that explains these in detail). Each of these network layers provides a different restriction and/or guarantee about the data at that layer. The protocols at each network layer generally have their own packet formats, headers, and layout.

The seven traditional layers of a network are divided into two groups: upper layers and lower layers. The sockets interface provides a uniform API to the lower layers of a network, and allows you to implement upper layers within your sockets application. Further, application data formats may themselves constitute further layers; for example, SOAP is built on top of XML, and ebXML may itself utilize SOAP. In any case, anything past layer 4 is outside the scope of this tutorial.

What do sockets do?

While the sockets interface theoretically allows access to *protocol families* other than IP, in practice, every network layer you use in your sockets application will use IP. For this tutorial we only look at IPv4; in the future IPv6 will become important also, but the principles are the same. At the transport layer, sockets support two specific protocols: TCP (transmission control protocol) and UDP (user datagram protocol).

Sockets cannot be used to access lower (or higher) network layers; for example, a socket application does not know whether it is running over Ethernet, token ring, or a dial-up connection. Nor does the socket's pseudo-layer know anything about higher-level protocols like NFS, HTTP, FTP, and the like (except in the sense that you might yourself write a sockets application that implements those higher-level protocols).

At times, the sockets interface is not your best choice for a network programming API. Specifically, many excellent libraries exist (in various languages) to use higher-level protocols directly, without your having to worry about the details of sockets; the libraries handle those details for you. While there is nothing wrong with writing you own SSH client, for example, there is no need to do so simply to let an application transfer data securely. Lower-level layers than those addressed by sockets fall pretty much in the domain of device driver programming.

IP, TCP, and UDP

As indicated above, when you program a sockets application, you have a choice to make between using TCP and using UDP. Each has its own benefits and disadvantages.

TCP is a stream protocol, while UDP is a datagram protocol. In other words, TCP establishes a continuous open connection between a client and a server, over which bytes may be written (and correct order guaranteed) for the life of the connection. However, bytes written over TCP have no built-in structure, so higher-level protocols are required to delimit any data records and fields within the transmitted bytestream.

UDP, on the other hand, does not require a connection to be established between client and server; it simply transmits a message between addresses. A nice feature of UDP is that its packets are self-delimiting; that is, each datagram indicates exactly where it begins and ends. A possible disadvantage of UDP, however, is that it provides no guarantee that packets will arrive in order, or even at all. Higher-level protocols built on top of UDP may, of course, provide handshaking and acknowledgments.

A useful analogy for understanding the difference between TCP and UDP is the difference between a telephone call and posted letters. The telephone call is not active until the caller "rings" the receiver and the receiver picks up. The telephone channel remains alive as long as the parties stay on the call, but they are free to say as much or as little as they wish to during the call. All remarks from either party occur in temporal order. On the other hand, when you send a letter, the post office starts delivery without any assurance the recipient exists, nor any strong guarantee about how long delivery will take. The recipient may receive various letters in a different order than they were sent, and the sender may receive mail interspersed in time with those she sends. Unlike with the postal service (ideally, anyway), undeliverable mail always goes to the dead letter office, and is not returned to sender.

Peers, ports, names, and addresses

Beyond the protocol, TCP or UDP, there are two things a peer (a client or server) needs to know about the machine it communicates with: an IP address and a port. An IP address is a 32-bit data value, usually represented for humans in "dotted quad" notation, such as `64.41.64.172`. A port is a 16-bit data value, usually simply represented as a number less than 65536, most often one in the tens or hundreds range. An IP address gets a packet *to* a machine; a port lets the machine decide which process/service (if any) to direct it to. That is a slight simplification, but the idea is correct.

The above description is almost right, but it misses something. Most of the time when humans think about an Internet host (peer), we do not remember a number like `64.41.64.172`, but instead a name like `gnosis.cx`. To find the IP address associated with a particular host name, usually you use a Domain Name Server, but sometimes local lookups are used first (often via the contents of `/etc/hosts`). For this tutorial, we will generally just assume an IP address is available, but we'll discuss coding name/address lookups next.

Host name resolution

The command-line utility `nslookup` can be used to find a host IP address from a symbolic name. Actually, a number of common utilities, such as `ping` or network configuration tools, do the same thing in passing. But it is simple to do the same thing programmatically.

In Python or other very-high-level scripting languages, writing a utility program to find a host IP address is trivial:

```
#!/usr/bin/env python
"USAGE: nslookup.py <inet_address>"
import socket, sys
print socket.gethostbyname(sys.argv[1])
```

The trick is using a wrapped version of the same `gethostbyname())` function we also find in C. Usage is as simple as:

```
$ ./nslookup.py gnosis.cx
64.41.64.172
```

In C, that standard library call `gethostbyname()` is used for name lookup. Below is a simple implementation of `nslookup` as a command-line tool; adapting it for use in a larger application is straightforward. Of course, C is a bit more finicky than Python is.

```
/* Bare nslookup utility (w/ minimal error checking) */
#include <stdio.h>          /* stderr, stdout */
#include <netdb.h>          /* hostent struct, gethostbyname() */
#include <arpa/inet.h>      /* inet_ntoa() to format IP address */
#include <netinet/in.h>     /* in_addr structure */

int main(int argc, char **argv) {
  struct hostent *host;     /* host information */
  struct in_addr h_addr;    /* Internet address */
  if (argc != 2) {
    fprintf(stderr, "USAGE: nslookup <inet_address>\n");
    exit(1);
  }
  if ((host = gethostbyname(argv[1])) == NULL) {
    fprintf(stderr, "(mini) nslookup failed on '%s'\n", argv[1]);
    exit(1);
  }
  h_addr.s_addr = *((unsigned long *) host-> h_addr_list[0]);
  fprintf(stdout, "%s\n", inet_ntoa(h_addr));
  exit(0);
}
```

Notice that the returned value from `gethostbyname()` is a `hostent` structure that describes the name's host. The member `host-> h_addr_list` contains a list of addresses, each of which is a 32-bit value in "network byte order"; in other words, the endianness may or may not be machine-native order. In order to convert to dotted-quad form, use the function `inet_ntoa()`.

Section 3. Writing a client application in C

The steps in writing a socket client

My examples for both clients and servers will use one of the simplest possible applications: one that sends data and receives the exact same thing back. In fact, many machines run an "echo server" for debugging purposes; this is convenient for our initial client, since it can be used before we get to the server portion (assuming you have a machine with `echod` running).

I would like to acknowledge the book *TCP/IP Sockets in C* by Donahoo and Calvert (see Resources). I have adapted several examples that they present. I recommend the book, but admittedly, echo servers/clients will come early in most presentations of sockets programming.

The steps involved in writing a client application differ slightly between TCP and UDP clients. In both cases, you first create the socket; in the TCP case only, you next establish a connection to the server; next you send some data to the server; then receive data back; perhaps the sending and receiving alternates for a while; finally, in the TCP case, you close the connection.

A TCP echo client (client setup)

First we will look at a TCP client; in Part 2 of this tutorial series, we will make some adjustments to do (roughly) the same thing with UDP. Let's look at the first few lines: some includes, and creating the socket:

```
#include <stdio.h>
#include <sys/socket.h>
#include <arpa/inet.h>
#include <stdlib.h>
#include <string.h>
#include <unistd.h>
#include <netinet/in.h>

#define BUFFSIZE 32
void Die(char *mess) { perror(mess); exit(1); }
```

There is not too much to the setup. A particular buffer size is allocated, which limits the amount of data echo'd at each pass (but we loop through multiple passes, if needed). A small error function is also defined.

A TCP echo client (creating the socket)

The arguments to the `socket()` call decide the type of socket: `PF_INET` just means it uses IP (which you always will); `SOCK_STREAM` and `IPPROTO_TCP` go together for a TCP socket.

```
int main(int argc, char *argv[]) {
int sock;
struct sockaddr_in echoserver;
char buffer[BUFFSIZE];
unsigned int echolen;
int received = 0;

if (argc != 4) {
  fprintf(stderr, "USAGE: TCPecho <server_ip> <word> <port>\n");
  exit(1);
}
/* Create the TCP socket */
if ((sock = socket(PF_INET, SOCK_STREAM, IPPROTO_TCP)) < 0) {
  Die("Failed to create socket");
}
```

The value returned is a socket handle, which is similar to a file handle; specifically, if the socket creation fails, it will return -1 rather than a positive-numbered handle.

A TCP echo client (establish connection)

Now that we have created a socket handle, we need to establish a connection with the server. A connection requires a `sockaddr` structure that describes the server. Specifically, we need to specify the server and port to connect to using `echoserver.sin_addr.s_addr` and `echoserver.sin_port`. The fact that we are using an IP address is specified with `echoserver.sin_family`, but this will always be set to `AF_INET`.

```
/* Construct the server sockaddr_in structure */
memset(&echoserver, 0, sizeof(echoserver));       /* Clear struct */
echoserver.sin_family = AF_INET;                  /* Internet/IP */
echoserver.sin_addr.s_addr = inet_addr(argv[1]);  /* IP address */
echoserver.sin_port = htons(atoi(argv[3]));       /* server port */
/* Establish connection */
if (connect(sock,
            (struct sockaddr *) &echoserver,
            sizeof(echoserver)) < 0) {
  Die("Failed to connect with server");
}
```

As with creating the socket, the attempt to establish a connection will return -1 if the attempt fails. Otherwise, the socket is now ready to accept sending and receiving data. See Resources for a reference on port numbers.

A TCP echo client (send/receive data)

Now that the connection is established, we are ready to send and receive data. A call to `send()` takes as arguments the socket handle itself, the string to send, the length of the sent string (for verification), and a flag argument. Normally the flag is the default value 0. The return value of the `send()` call is the number of bytes successfully sent.

```
/* Send the word to the server */
echolen = strlen(argv[2]);
if (send(sock, argv[2], echolen, 0) != echolen) {
  Die("Mismatch in number of sent bytes");
}
/* Receive the word back from the server */
fprintf(stdout, "Received: ");
while (received < echolen) {
  int bytes = 0;
```

```
                if ((bytes = recv(sock, buffer, BUFFSIZE-1, 0)) < 1) {
                  Die("Failed to receive bytes from server");
                }
                received += bytes;
                buffer[bytes] = '\0';        /* Assure null terminated string */
                fprintf(stdout, buffer);
              }
```

The `rcv()` call is not guaranteed to get everything in-transit on a particular call; it simply blocks until it gets *something*. Therefore, we loop until we have gotten back as many bytes as were sent, writing each partial string as we get it. Obviously, a different protocol might decide when to terminate receiving bytes in a different manner (perhaps a delimiter within the bytestream).

A TCP echo client (wrapup)

Calls to both `send()` and `recv()` block by default, but it is possible to change socket options to allow non-blocking sockets. However, this tutorial will not cover details of creating non-blocking sockets, nor such other details used in production servers as forking, threading, or general asynchronous processing (built on non-blocking sockets). These issues are covered in Part 2.

At the end of the process, we want to call `close()` on the socket, much as we would with a file handle:

```
          fprintf(stdout, "\n");
          close(sock);
          exit(0);
        }
```

Section 4. Writing a server application in C

The steps in writing a socket server

A socket server is a bit more complicated than a client, mostly because a server usually needs to be able to handle multiple client requests. Basically, there are two aspects to a server: handling each established connection, and listening for connections to establish.

In our example, and in most cases, you can split the handling of a particular connection into support function, which looks quite a bit like how a TCP client application does. We name that function `HandleClient()`.

Listening for new connections is a bit different from client code. The trick is that the socket you initially create and bind to an address and port is not the actually connected socket. This initial socket acts more like a socket factory, producing new connected sockets as needed. This arrangement has an advantage in enabling fork'd, threaded, or asynchronously dispatched handlers (using `select()`); however, for this first tutorial we will only handle pending connected sockets in synchronous order.

A TCP echo server (application setup)

Our echo server starts out with pretty much the same few `#include` s as the client did, and defines some constants and an error-handling function:

```
#include <stdio.h>
#include <sys/socket.h>
#include <arpa/inet.h>
#include <stdlib.h>
#include <string.h>
#include <unistd.h>
#include <netinet/in.h>

#define MAXPENDING 5    /* Max connection requests */
#define BUFFSIZE 32
void Die(char *mess) { perror(mess); exit(1); }
```

The `BUFFSIZE` constant limits the data sent per loop. The `MAXPENDING` constant limits the number of connections that will be queued at a time (only one will be *serviced* at a time in our simple server). The `Die()` function is the same as in our client.

A TCP echo server (the connection handler)

The handler for echo connections is straightforward. All it does is receive any initial bytes available, then cycles through sending back data and receiving more data. For short echo strings (particularly if less than `BUFFSIZE`) and typical connections, only one pass through the `while` loop will occur. But the underlying sockets interface (and TCP/IP) does not make any guarantees about how the bytestream will be split between calls to `recv()`.

```
void HandleClient(int sock) {
  char buffer[BUFFSIZE];
  int received = -1;
  /* Receive message */
```

```
      if ((received = recv(sock, buffer, BUFFSIZE, 0)) < 0) {
        Die("Failed to receive initial bytes from client");
      }
      /* Send bytes and check for more incoming data in loop */
      while (received > 0) {
        /* Send back received data */
        if (send(sock, buffer, received, 0) != received) {
          Die("Failed to send bytes to client");
        }
        /* Check for more data */
        if ((received = recv(sock, buffer, BUFFSIZE, 0)) < 0) {
          Die("Failed to receive additional bytes from client");
        }
      }
      close(sock);
    }
```

The socket that is passed in to the handler function is one that already connected to the requesting client. Once we are done with echoing all the data, we should close this socket; the parent server socket stays around to spawn new children, like the one just closed.

A TCP echo server (configuring the server socket)

As outlined before, creating a socket has a bit different purpose for a server than for a client. Creating the socket has the same syntax it did in the client, but the structure `echoserver` is set up with information about the server itself, rather than about the peer it wants to connect to. You usually want to use the special constant `INADDR_ANY` to enable receipt of client requests on any IP address the server supplies; in principle, such as in a multi-hosting server, you could specify a particular IP address instead.

```
    int main(int argc, char *argv[]) {
      int serversock, clientsock;
      struct sockaddr_in echoserver, echoclient;

      if (argc != 2) {
        fprintf(stderr, "USAGE: echoserver <port>\n");
        exit(1);
      }
      /* Create the TCP socket */
      if ((serversock = socket(PF_INET, SOCK_STREAM, IPPROTO_TCP)) < 0) {
        Die("Failed to create socket");
      }
      /* Construct the server sockaddr_in structure */
      memset(&echoserver, 0, sizeof(echoserver));       /* Clear struct */
      echoserver.sin_family = AF_INET;                  /* Internet/IP */
      echoserver.sin_addr.s_addr = htonl(INADDR_ANY);   /* Incoming addr */
      echoserver.sin_port = htons(atoi(argv[1]));       /* server port */
```

Notice that both IP address and port are converted to network byte order for the `sockaddr_in` structure. The reverse functions to return to native byte order are `ntohs()` and `ntohl()`. These functions are no-ops on some platforms, but it is still wise to use them for cross-platform compatibility.

A TCP echo server (binding and listening)

Whereas the client application `connect()` 'd to a server's IP address and port, the server `bind()` s to its own address and port:

```
/* Bind the server socket */
if (bind(serversock, (struct sockaddr *) &echoserver,
                             sizeof(echoserver)) < 0) {
  Die("Failed to bind the server socket");
}
/* Listen on the server socket */
if (listen(serversock, MAXPENDING) < 0) {
  Die("Failed to listen on server socket");
}
```

Once the server socket is bound, it is ready to `listen()`. As with most socket functions, both `bind()` and `listen()` return -1 if they have a problem. Once a server socket is listening, it is ready to `accept()` client connections, acting as a factory for sockets on each connection.

A TCP echo server (socket factory)

Creating new sockets for client connections is the crux of a server. The function `accept()` does two important things: it returns a socket pointer for the new socket; and it populates the `sockaddr_in` structure pointed to, in our case, by `echoclient`.

```
  /* Run until cancelled */
  while (1) {
    unsigned int clientlen = sizeof(echoclient);
    /* Wait for client connection */
    if ((clientsock =
         accept(serversock, (struct sockaddr *) &echoclient,
                &clientlen)) < 0) {
      Die("Failed to accept client connection");
    }
    fprintf(stdout, "Client connected: %s\n",
                    inet_ntoa(echoclient.sin_addr));
    HandleClient(clientsock);
  }
}
```

We can see the populated structure in `echoclient` with the `fprintf()` call that accesses the client IP address. The client socket pointer is passed to `HandleClient()`, which we saw at the start of this section.

Section 5. Writing socket applications in Python

The socket and SocketServer module

Python's standard module `socket` provides almost exactly the same range of capabilities you would find in C sockets. However, the interface is generally more flexible, largely because of the benefits of dynamic typing. Moreover, an object-oriented style is also used. For example, once you create a socket object, methods like `.bind()`, `.connect()`, and `.send()` are methods of that object, rather than global functions operating on a socket pointer.

At a higher level than `socket`, the module `SocketServer` provides a framework for writing servers. This is still relatively low level, and higher-level interfaces are available for serving higher-level protocols, such as `SimpleHTTPServer`, `DocXMLRPCServer`, and `CGIHTTPServer`.

A Python TCP echo client

Let's look at the complete client. At first brush, we seem to have left out some of the error-catching code from the C version. But since Python raises descriptive errors for every situation that we checked for in the C echo client, we can let the built-in exceptions do our work for us. Of course, if we wanted the precise wording of errors that we had before, we would have to add a few `try`/`except` clauses around the calls to methods of the socket object.

```
#!/usr/bin/env python
"USAGE: echoclient.py <server> <word> <port>"
from socket import *    # import *, but we'll avoid name conflict
import sys
if len(sys.argv) != 4:
    print __doc__
    sys.exit(0)
sock = socket(AF_INET, SOCK_STREAM)
sock.connect((sys.argv[1], int(sys.argv[3])))
message = sys.argv[2]
messlen, received = sock.send(message), 0
if messlen != len(message)
    print "Failed to send complete message"
print "Received: ",
while received < messlen:
    data = sock.recv(32)
    sys.stdout.write(data)
    received += len(data)
print
sock.close()
```

While shorter, the Python client is somewhat more powerful. Specifically, the address we feed to a `. connect()` call can be either a dotted-quad IP address or a symbolic name, without need for extra lookup work; for example:

```
$ ./echoclient 192.168.2.103 foobar 7
Received: foobar
$ ./echoclient.py fury.gnosis.lan foobar 7
Received: foobar
```

We also have a choice between the methods `. send()` and `. sendall()`. The former sends as many bytes as it can at once, the latter sends the whole message (or raises an exception if it cannot). For this client, we indicate if the whole message was not sent, but proceed with getting back as much as actually was sent.

A Python TCP echo server (SocketServer)

The simplest way to write an echo server in Python is using the `SocketServer` module. It is so easy as to almost seem like cheating. Later, we will spell out the lower-level version that follows the C implementation. For now, let's see how quick it can be:

```
#!/usr/bin/env python
"USAGE: echoserver.py <port>"
from SocketServer import BaseRequestHandler, TCPServer
import sys, socket

class EchoHandler(BaseRequestHandler):
    def handle(self):
        print "Client connected:", self.client_address
        self.request.sendall(self.request.recv(2**16))
        self.request.close()

if len(sys.argv) != 2:
    print __doc__
else:
    TCPServer(('',int(sys.argv[1])), EchoHandler).serve_forever()
```

The only thing we need to provide is a child of `SocketServer.BaseRequestHandler` that has a `. handle()` method. The `self` instance has some useful attributes, such as `. client_address`, and `. request`, which is itself a connected socket object.

A Python TCP echo server (socket)

If we wish to do it "the hard way," and gain a bit more fine-tuned control, we can write almost exactly our C echo server in Python (but in fewer lines):

```
#!/usr/bin/env python
"USAGE: echoclient.py <server> <word> <port>"
from socket import *    # import *, but we'll avoid name conflict
import sys

def handleClient(sock):
    data = sock.recv(32)
    while data:
        sock.sendall(data)
        data = sock.recv(32)
    sock.close()

if len(sys.argv) != 2:
    print __doc__
else:
    sock = socket(AF_INET, SOCK_STREAM)
    sock.bind(('',int(sys.argv[1])))
    sock.listen(5)
    while 1:    # Run until cancelled
        newsock, client_addr = sock.accept()
        print "Client connected:", client_addr
        handleClient(newsock)
```

In truth, this "hard way" still isn't very hard. But as in the C implementation, we manufacture new connected sockets using `. listen()`, and call our handler for each such connection.

Section 6. Summary

The server and client presented in this tutorial are simple, but they show everything essential to writing TCP sockets applications. If the data transmitted is more complicated, or the interaction between peers (client and server) is more sophisticated in your application, that is just a matter of additional application programming. The data exchanged will still follow the same pattern of `connect()` and `bind()`, then `send()` and `recv()`.

One thing this tutorial did not get to, except in brief summary at the start, is usage of UDP sockets. TCP is more common, but it is important to also understand UDP sockets as an option for your application. Part 2 of this tutorial series looks at UDP, as well as implementing sockets applications in Python, and some other intermediate topics.

Resources

Learn

- Programming Linux sockets, Part 2: Using UDP, the next tutorial in this series, looks at UDP sockets as an option for your application, and also covers implementing sockets applications in Python as well as other intermediate topics.
- A good introduction to sockets programming in C is *TCP/IP Sockets in C* , by Michael J. Donahoo and Kenneth L. Calvert (Morgan-Kaufmann, 2001). Examples and more information are available on the book's Author pages.
- The UNIX Systems Support Group document Network Layers explains the functions of the lower network layers.
- The Transmission Control Protocol (TCP) is covered in RFC 793.
- The User Datagram Protocol (UDP) is the subject of RFC 768.
- You can find a list of widely used port assignments at the IANA (Internet Assigned Numbers Authority) Web site.
- "Understanding Sockets in Unix, NT, and Java" (developerWorks, June 1998) illustrates fundamental sockets principles with sample source code in C and in Java.
- The Sockets section from the AIX C Programming book *Communications Programming Concepts* goes into depth on a number of related issues.
- Volume 2 of the *AIX 5L Version 5.2 Technical Reference* focuses on Communications, including, of course, a great deal on sockets programming.
- Sockets, network layers, UDP, and much more are also discussed in the conversational Beej's Guide to Network Programming.
- You may find Gordon McMillan's Socket Programming HOWTO and Jim Frost's BSD Sockets: A Quick and Dirty Primer useful as well.
- Find more tutorials for Linux developers in the developerWorks Linux one.
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