15-213

"The course that gives CMU its Zip!"

Network Programming
April 12, 2005

Topics

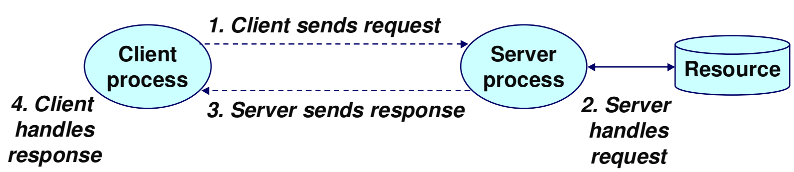
- Programmer's view of the Internet (review)
- Sockets interface
- Writing clients and servers

`23-network.ppt`

A Client-Server Transaction

Most network applications are based on the client-server model:

- A *server* process and one or more *client* processes
- Server manages some *resource*.
- Server provides *service* by manipulating resource for clients.



Note: clients and servers are processes running on hosts (can be the same or different hosts).

A Programmer's View of the Internet

1. Hosts are mapped to a set of 32-bit *IP addresses*.
   - 128.2.203.179

2. The set of IP addresses is mapped to a set of identifiers called Internet *domain names*.
   - 128.2.203.179 is mapped to www.cs.cmu.edu

3. A process on one Internet host can communicate with a process on another Internet host over a *connection*.

1. IP Addresses

32-bit IP addresses are stored in an *IP address struct*

- IP addresses are always stored in memory in network byte order (big-endian byte order)
- True in general for any integer transferred in a packet header from one machine to another.
  - E.g., the port number used to identify an Internet connection.

```
/* Internet address structure */
struct in_addr {
    unsigned int s_addr; /* network byte order (big-endian) */
};
```

Handy network byte-order conversion functions:

`htonl`: convert `long int` from host to network byte order.
`htons`: convert `short int` from host to network byte order.
`ntohl`: convert `long int` from network to host byte order.
`ntohs`: convert `short int` from network to host byte order.

2. Domain Naming System (DNS)

The Internet maintains a mapping between IP addresses and domain names in a huge worldwide distributed database called *DNS*.

- Conceptually, programmers can view the DNS database as a collection of millions of *host entry structures*:

```
/* DNS host entry structure */
struct hostent {
   char   *h_name;        /* official domain name of host */
   char   **h_aliases;    /* null-terminated array of domain names */
   int    h_addrtype;     /* host address type (AF_INET) */
   int    h_length;       /* length of an address, in bytes */
   char   **h_addr_list;  /* null-terminated array of in_addr structs */
};
```

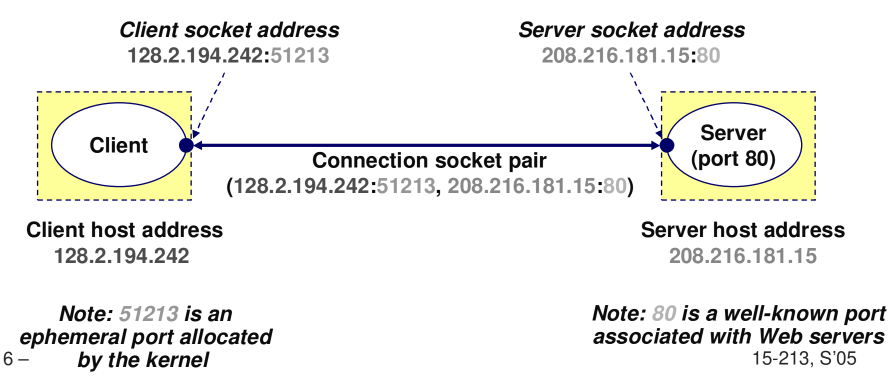
Functions for retrieving host entries from DNS:

- `gethostbyname`: query key is a DNS domain name.
- `gethostbyaddr`: query key is an IP address.

3. Internet Connections

Clients and servers communicate by sending streams of bytes over *connections*.

Connections are point-to-point, full-duplex (2-way communication), and reliable.



Clients

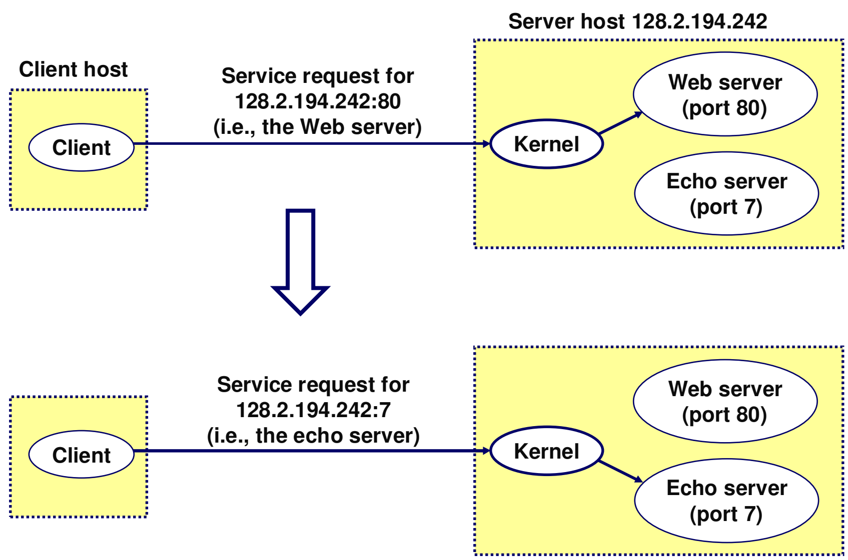
Examples of client programs

- Web browsers, `ftp`, `telnet`, `ssh`

How does a client find the server?

- The IP address in the server socket address identifies the host *(more precisely, an adapter on the host)*
- The (well-known) port in the server socket address identifies the service, and thus implicitly identifies the server process that performs that service.
- Examples of well know ports
  - Port 7: Echo server
  - Port 22: Ssh server
  - Port 23: Telnet server
  - Port 25: Mail server
  - Port 80: Web server

Using Ports to Identify Services



Servers

Servers are long-running processes (daemons).

- Created at boot-time (typically) by the init process (process 1)
- Run continuously until the machine is turned off.

Each server waits for requests to arrive on a well-known port associated with a particular service.

- Port 7: echo server
- Port 22: ssh server
- Port 23: telnet server
- Port 25: mail server
- Port 80: HTTP server

A machine that runs a server process is also often referred to as a “server.”

Server Examples

Web server (port 80)

- Resource: files/compute cycles (CGI programs)
- Service: retrieves files and runs CGI programs on behalf of the client

FTP server (20, 21)

- Resource: files
- Service: stores and retrieve files

See `/etc/services` for a comprehensive list of the services available on a Linux machine.

Telnet server (23)

- Resource: terminal
- Service: proxies a terminal on the server machine

Mail server (25)

- Resource: email “spool” file
- Service: stores mail messages in spool file

Sockets Interface

Created in the early 80's as part of the original Berkeley distribution of Unix that contained an early version of the Internet protocols.

Provides a user-level interface to the network.

Underlying basis for all Internet applications.

Based on client/server programming model.

Sockets

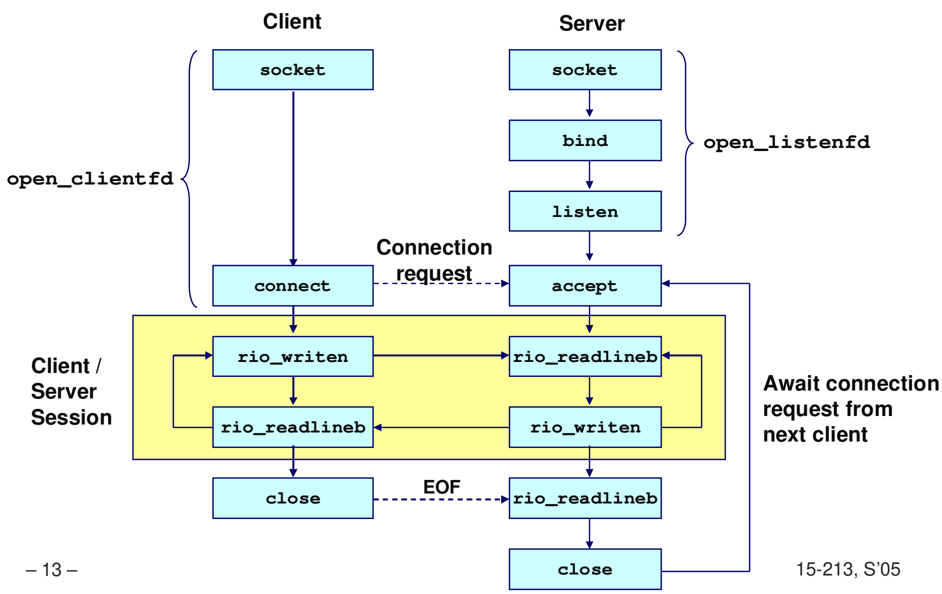
What is a socket?

- To the kernel, a socket is an endpoint of communication.
- To an application, a socket is a file descriptor that lets the application read/write from/to the network.
  - Remember: All Unix I/O devices, including networks, are modeled as files.

Clients and servers communicate with each other by reading from and writing to socket descriptors.

The main distinction between regular file I/O and socket I/O is how the application "opens" the socket descriptors.

Overview of the Sockets Interface

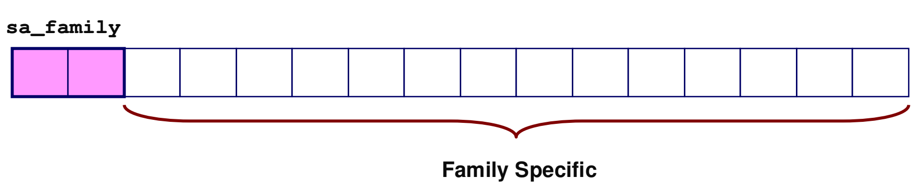


Socket Address Structures

Generic socket address:

- For address arguments to `connect`, `bind`, and `accept`.
- Necessary only because C did not have generic (`void *`) pointers when the sockets interface was designed.

```
struct sockaddr {
  unsigned short  sa_family;    /* protocol family */
  char            sa_data[14];  /* address data.   */
};
```

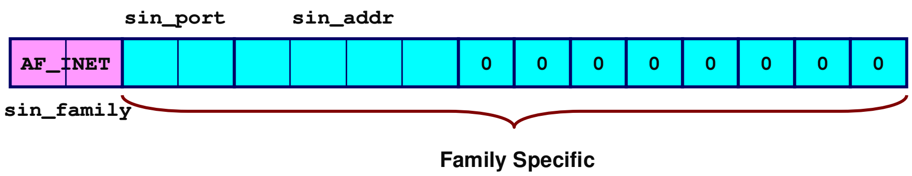


Socket Address Structures

Internet-specific socket address:

- Must cast (`sockaddr_in *`) to (`sockaddr *`) for `connect`, `bind`, and `accept`.

```
struct sockaddr_in  {
  unsigned short  sin_family;  /* address family (always AF_INET) */
  unsigned short  sin_port;    /* port num in network byte order */
  struct in_addr  sin_addr;    /* IP addr in network byte order */
  unsigned char   sin_zero[8]; /* pad to sizeof(struct sockaddr) */
};
```



Example: Echo Client and Server

On Server

```
bass> echoserver 5000
server established connection with KITTYHAWK.CMCL (128.2.194.242)
server received 4 bytes: 123
server established connection with KITTYHAWK.CMCL (128.2.194.242)
server received 7 bytes: 456789
...
```

On Client

```
kittyhawk> echoclient bass 5000
Please enter msg: 123
Echo from server: 123

kittyhawk> echoclient bass 5000
Please enter msg: 456789
Echo from server: 456789
kittyhawk>
```

Echo Client Main Routine

```
#include "csapp.h"

/* usage: ./echoclient host port */
int main(int argc, char **argv)
{
    int clientfd, port;
    char *host, buf[MAXLINE];
    rio_t rio;
    host = argv[1];  port = atoi(argv[2]);
    clientfd = Open_clientfd(host, port);
    Rio_readinitb(&rio, clientfd);
    printf("type:"); fflush(stdout);
    while (Fgets(buf, MAXLINE, stdin) != NULL) {
        Rio_writen(clientfd, buf, strlen(buf));
        Rio_readlineb(&rio, buf, MAXLINE);
        printf("echo:");
        Fputs(buf, stdout);
        printf("type:"); fflush(stdout);
    }
    Close(clientfd);
    exit(0);
}
```

Send line to server

Receive line from server

Echo Client: `open_clientfd`

This function opens a connection from the client to the server at `hostname:port`

```
int open_clientfd(char *hostname, int port)
{
  int clientfd;
  struct hostent *hp;
  struct sockaddr_in serveraddr;

  if ((clientfd = socket(AF_INET, SOCK_STREAM, 0)) < 0)
    return -1; /* check errno for cause of error */

  /* Fill in the server's IP address and port */
  if ((hp = gethostbyname(hostname)) == NULL)
    return -2; /* check h_errno for cause of error */
  bzero((char *) &serveraddr, sizeof(serveraddr));
  serveraddr.sin_family = AF_INET;
  bcopy((char *)hp->h_addr,
        (char *)&serveraddr.sin_addr.s_addr, hp->h_length);
  serveraddr.sin_port = htons(port);

  /* Establish a connection with the server */
  if (connect(clientfd, (SA *) &serveraddr, sizeof(serveraddr)) < 0)
    return -1;
  return clientfd;
}
```

Echo Client: `open_clientfd` (`socket`)

`socket` creates a socket descriptor on the client

- Just allocates & initializes some internal data structures
- `AF_INET`: indicates that the socket is associated with Internet protocols.
- `SOCK_STREAM`: selects a reliable byte stream connection
  - Provided by TCP

```
int clientfd;  /* socket descriptor */

if ((clientfd = socket(AF_INET, SOCK_STREAM, 0)) < 0)
    return -1; /* check errno for cause of error */

... (more)
```


Echo Client: `open_clientfd` (`gethostbyname`)

The client then builds the server's Internet address.

```
int clientfd;                  /* socket descriptor */
struct hostent *hp;            /* DNS host entry */
struct sockaddr_in serveraddr; /* server's IP address */

...

/* fill in the server's IP address and port */
if ((hp = gethostbyname(hostname)) == NULL)
    return -2; /* check h_errno for cause of error */
bzero((char *) &serveraddr, sizeof(serveraddr));
serveraddr.sin_family = AF_INET;
serveraddr.sin_port = htons(port);
bcopy((char *)hp->h_addr_list[0],
      (char *)&serveraddr.sin_addr.s_addr, hp->h_length);
```

Check this out!

A Careful Look at bcopy Arguments

```
/* DNS host entry structure */
struct hostent {
   . . .
   int    h_length;      /* length of an address, in bytes */
   char   **h_addr_list; /* null-terminated array of in_addr structs */
};
```

```
struct sockaddr_in  {
   . . .
   struct in_addr  sin_addr;    /* IP addr in network byte order */
   . . .
};
```

```
/* Internet address structure */
struct in_addr {
    unsigned int s_addr; /* network byte order (big-endian) */
};
```

```
struct hostent *hp;              /* DNS host entry */
struct sockaddr_in serveraddr; /* server's IP address */
...
bcopy((char *)hp->h_addr_list[0], /* src, dest */
      (char *)&serveraddr.sin_addr.s_addr, hp->h_length);
```


Echo Client: open_clientfd (connect)

Finally the client creates a connection with the server.

- Client process suspends (blocks) until the connection is created.
- After resuming, the client is ready to begin exchanging messages with the server via Unix I/O calls on descriptor `clientfd`.

```
  int clientfd;                    /* socket descriptor */
  struct sockaddr_in serveraddr;   /* server address */
  typedef struct sockaddr SA;      /* generic sockaddr */
...
  /* Establish a connection with the server */
  if (connect(clientfd, (SA *)&serveraddr, sizeof(serveraddr)) < 0)
    return -1;
  return clientfd;
}
```

Echo Server: Main Routine

```
int main(int argc, char **argv) {
    int listenfd, connfd, port, clientlen;
    struct sockaddr_in clientaddr;
    struct hostent *hp;
    char *haddrp;

    port = atoi(argv[1]); /* the server listens on a port passed
                             on the command line */
    listenfd = open_listenfd(port);

    while (1) {
        clientlen = sizeof(clientaddr);
        connfd = Accept(listenfd, (SA *)&clientaddr, &clientlen);
        hp = Gethostbyaddr((const char *)&clientaddr.sin_addr.s_addr,
                           sizeof(clientaddr.sin_addr.s_addr), AF_INET);
        haddrp = inet_ntoa(clientaddr.sin_addr);
        printf("server connected to %s (%s)\n", hp->h_name, haddrp);
        echo(connfd);
        Close(connfd);
    }
}
```


Echo Server: `open_listenfd`

```
int open_listenfd(int port)
{
    int listenfd, optval=1;
    struct sockaddr_in serveraddr;

    /* Create a socket descriptor */
    if ((listenfd = socket(AF_INET, SOCK_STREAM, 0)) < 0)
        return -1;

    /* Eliminates "Address already in use" error from bind. */
    if (setsockopt(listenfd, SOL_SOCKET, SO_REUSEADDR,
                   (const void *)&optval , sizeof(int)) < 0)
        return -1;

... (more)
```

Echo Server: `open_listenfd` (cont)

```
...

  /* Listenfd will be an endpoint for all requests to port
       on any IP address for this host */
    bzero((char *) &serveraddr, sizeof(serveraddr));
    serveraddr.sin_family = AF_INET;
    serveraddr.sin_addr.s_addr = htonl(INADDR_ANY);
    serveraddr.sin_port = htons((unsigned short)port);
    if (bind(listenfd, (SA *)&serveraddr, sizeof(serveraddr)) < 0)
        return -1;

    /* Make it a listening socket ready to accept
       connection requests */
    if (listen(listenfd, LISTENQ) < 0)
        return -1;

   return listenfd;
}
```


Echo Server: `open_listenfd` (`socket`)

`socket` creates a socket descriptor on the server.

- `AF_INET`: indicates that the socket is associated with Internet protocols.
- `SOCK_STREAM`: selects a reliable byte stream connection (TCP)

```
int listenfd; /* listening socket descriptor */

/* Create a socket descriptor */
if ((listenfd = socket(AF_INET, SOCK_STREAM, 0)) < 0)
    return -1;
```

Echo Server: `open_listenfd` (`setsockopt`)

The socket can be given some attributes.

```
...
/* Eliminates "Address already in use" error from bind(). */
if (setsockopt(listenfd, SOL_SOCKET, SO_REUSEADDR,
               (const void *)&optval , sizeof(int)) < 0)
    return -1;
```

Handy trick that allows us to rerun the server immediately after we kill it.

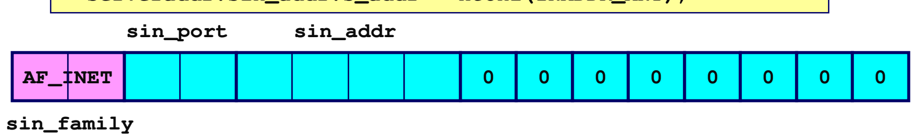
- Otherwise we would have to wait about 15 secs.
- Eliminates "Address already in use" error from `bind()`.

Strongly suggest you do this for all your servers to simplify debugging.

Echo Server: `open_listenfd` (initialize socket address)

Next, we initialize the socket with the server's Internet address (IP address and port)

```
  struct sockaddr_in serveraddr; /* server's socket addr */
...
  /* listenfd will be an endpoint for all requests to port
     on any IP address for this host */
  bzero((char *) &serveraddr, sizeof(serveraddr));
  serveraddr.sin_family = AF_INET;
  serveraddr.sin_port = htons((unsigned short)port);
  serveraddr.sin_addr.s_addr = htonl(INADDR_ANY);
```



IP addr and port stored in network (big-endian) byte order

Echo Server: `open_listenfd` (`bind`)

`bind` associates the socket with the socket address we just created.

```
int listenfd;                  /* listening socket */
struct sockaddr_in serveraddr; /* server's socket addr */

...
  /* listenfd will be an endpoint for all requests to port
     on any IP address for this host */
  if (bind(listenfd, (SA *)&serveraddr, sizeof(serveraddr)) < 0)
      return -1;
```


Echo Server: `open_listenfd` (`listen`)

`listen` indicates that this socket will accept connection (`connect`) requests from clients.

```
int listenfd; /* listening socket */

...
 /* Make it a listening socket ready to accept connection requests */
    if (listen(listenfd, LISTENQ) < 0)
        return -1;
    return listenfd;
}
```

We're finally ready to enter the main server loop that accepts and processes client connection requests.

Echo Server: Main Loop

The server loops endlessly, waiting for connection requests, then reading input from the client, and echoing the input back to the client.

```
main() {

   /* create and configure the listening socket */

   while(1) {
      /* Accept(): wait for a connection request */
      /* echo(): read and echo input lines from client til EOF */
      /* Close(): close the connection */
   }
}
```


Echo Server: `accept`

`accept()` blocks waiting for a connection request.

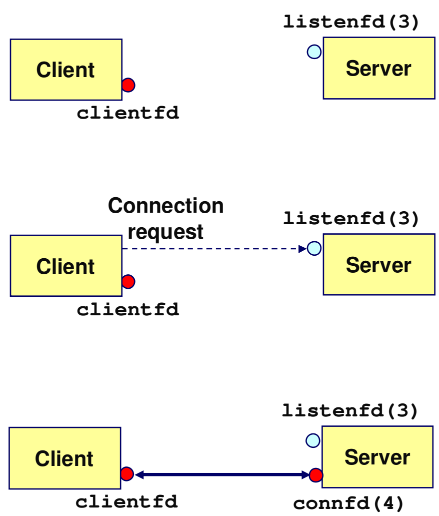
```
int listenfd; /* listening descriptor */
int connfd;   /* connected descriptor */
struct sockaddr_in clientaddr;
int clientlen;

clientlen = sizeof(clientaddr);
connfd = Accept(listenfd, (SA *)&clientaddr, &clientlen);
```

`accept` returns a *connected descriptor* (`connfd`) with the same properties as the *listening descriptor* (`listenfd`)

- **Returns when the connection between client and server is created and ready for I/O transfers.**
- **All I/O with the client will be done via the connected socket.**

`accept` also fills in client's IP address.

Echo Server: `accept` Illustrated



1. Server blocks in `accept`, waiting for connection request on listening descriptor `listenfd`.

2. Client makes connection request by calling and blocking in `connect`.

3. Server returns `connfd` from `accept`. Client returns from `connect`. Connection is now established between `clientfd` and `connfd`.

Connected vs. Listening Descriptors

Listening descriptor

- End point for client connection requests.
- Created once and exists for lifetime of the server.

Connected descriptor

- End point of the connection between client and server.
- A new descriptor is created each time the server accepts a connection request from a client.
- Exists only as long as it takes to service client.

Why the distinction?

- Allows for concurrent servers that can communicate over many client connections simultaneously.
  - E.g., Each time we receive a new request, we fork a child to handle the request.

Echo Server: Identifying the Client

The server can determine the domain name and IP address of the client.

```
struct hostent *hp;  /* pointer to DNS host entry */
char *haddrp;        /* pointer to dotted decimal string */

hp = Gethostbyaddr((const char *)&clientaddr.sin_addr.s_addr,
                   sizeof(clientaddr.sin_addr.s_addr), AF_INET);
haddrp = inet_ntoa(clientaddr.sin_addr);
printf("server connected to %s (%s)\n", hp->h_name, haddrp);
```


Echo Server: `echo`

The server uses RIO to read and echo text lines until EOF (end-of-file) is encountered.

- EOF notification caused by client calling `close(clientfd)`.
- IMPORTANT: EOF is a condition, not a particular data byte.

```
void echo(int connfd)
{
    size_t n;
    char buf[MAXLINE];
    rio_t rio;

    Rio_readinitb(&rio, connfd);
    while((n = Rio_readlineb(&rio, buf, MAXLINE)) != 0) {
        printf("server received %d bytes\n", n);
        Rio_writen(connfd, buf, n);
    }
}
```

Testing Servers Using `telnet`

The `telnet` program is invaluable for testing servers that transmit ASCII strings over Internet connections

- Our simple echo server
- Web servers
- Mail servers

Usage:

- `unix> telnet <host> <portnumber>`
- Creates a connection with a server running on *<host>* and listening on port *<portnumber>*.

Testing the Echo Server With `telnet`

```
bass> echoserver 5000
server established connection with KITTYHAWK.CMCL (128.2.194.242)
server received 5 bytes: 123
server established connection with KITTYHAWK.CMCL (128.2.194.242)
server received 8 bytes: 456789

kittyhawk> telnet bass 5000
Trying 128.2.222.85...
Connected to BASS.CMCL.CS.CMU.EDU.
Escape character is '^]'.
123
123
Connection closed by foreign host.
kittyhawk> telnet bass 5000
Trying 128.2.222.85...
Connected to BASS.CMCL.CS.CMU.EDU.
Escape character is '^]'.
456789
456789
Connection closed by foreign host.
kittyhawk>
```

For More Information

W. Richard Stevens, "Unix Network Programming: Networking APIs: Sockets and XTI", Volume 1, Second Edition, Prentice Hall, 1998.

- THE network programming bible.

Unix Man Pages

- Good for detailed information about specific functions

Complete versions of the echo client and server are developed in the text.

- Available from `csapp.cs.cmu.edu` course website
- You should compile and run them for yourselves to see how they work.
- Feel free to borrow any of this code.