Network Programming

15-213 / 18-213: Introduction to Computer Systems
21st Lecture, April. 4, 2012

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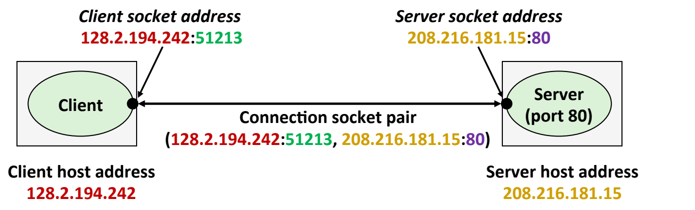
A Programmer's View of the Internet

- **Hosts are mapped to a set of 32-bit *IP addresses***
  - 128.2.217.13
- **The set of IP addresses is mapped to a set of identifiers called Internet *domain names***
  - 128.2.217.13 is mapped to www.cs.cmu.edu
- **A process on one Internet host can communicate with a process on another Internet host over a *connection***

Internet Connections

- **Clients and servers communicate by sending streams of bytes over *connections:***
  - Point-to-point, full-duplex (2-way communication), and reliable
- ***A socket* is an endpoint of a connection**
  - Socket address is an `IPaddress:port` pair
- **A *port* is a 16-bit integer that identifies a process:**
  - ***Ephemeral port:*** Assigned automatically on client when client makes a connection request
  - ***Well-known port:*** Associated with some service provided by a server (e.g., port 80 is associated with Web servers)
- **A connection is uniquely identified by the socket addresses of its endpoints (*socket pair*)**
  - `(cliaddr:cliport, servaddr:servport)`

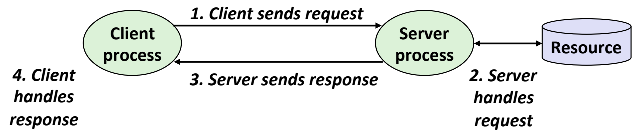
Anatomy of an Internet Connection



51213 is an ephemeral port allocated by the kernel

80 is a well-known port associated with Web servers

A Client-Server Transaction



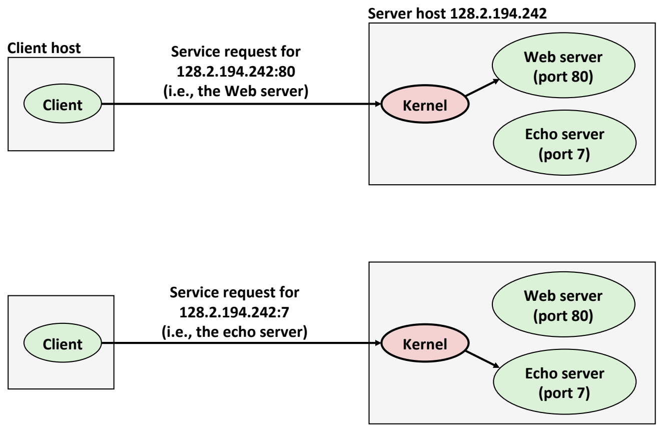
Note: clients and servers are processes running on hosts (can be the same or different hosts)

- **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
  - Server activated by request from client (vending machine analogy)

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 23: Telnet server
    - Port 25: Mail server
    - Port 80: Web server

Using Ports to Identify Services


Client host
Client
Service request for 128.2.194.242:80 (i.e., the Web server)
Server host 128.2.194.242
Kernel
Web server (port 80)
Echo server (port 7)
Client
Service request for 128.2.194.242:7 (i.e., the echo server)
Kernel
Web server (port 80)
Echo server (port 7)

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 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
- **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

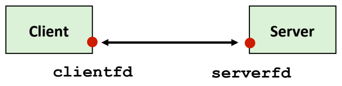
See `/etc/services` for a comprehensive list of the port mappings on a Linux machine

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**

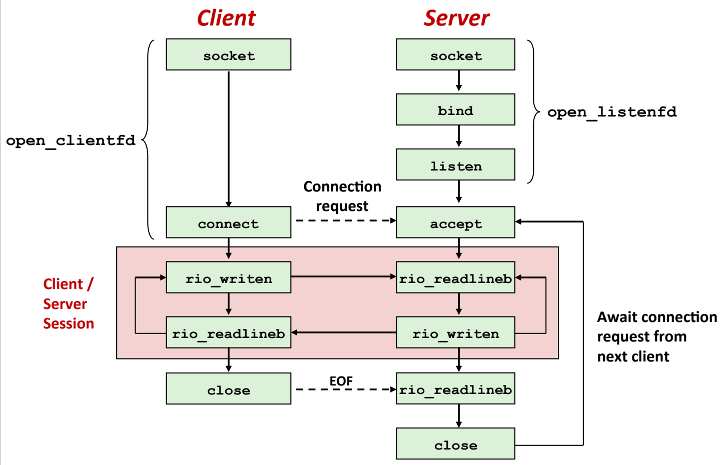
Sockets

- **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**

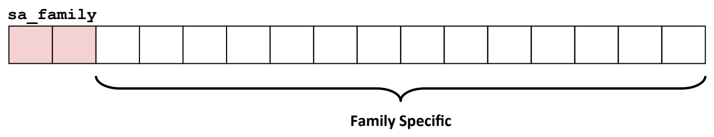
Overview of the Sockets Interface



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

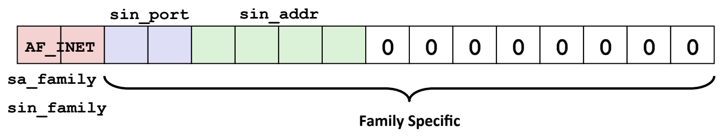
```
struct sockaddr {
  unsigned short  sa_family;    /* protocol family */
  char            sa_data[14];  /* address data.  */
};
```



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 Client **On Server**

```
greatwhite> ./echoserveri 15213
linux> echoclient greatwhite.ics.cs.cmu.edu 15213
server connected to BRYANT-TP4.VLSI.CS.CMU.EDU
(128.2.213.29), port 64690
type: hello there
server received 12 bytes
echo: HELLO THERE
type: ^D
Connection closed
```

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);
}
```

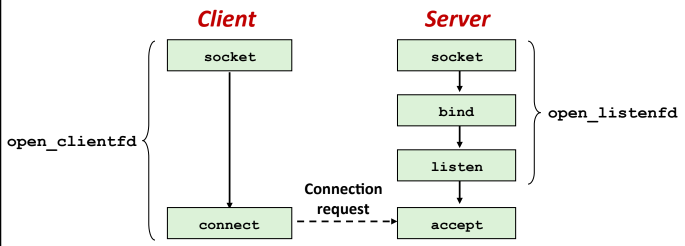
Read input line

Send line to server

Receive line from server

Print server response

Overview of the Sockets Interface



Echo Client: `open_clientfd`

```
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_list[0],
        (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;
}
```

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

Create socket

Create address

Establish connection

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

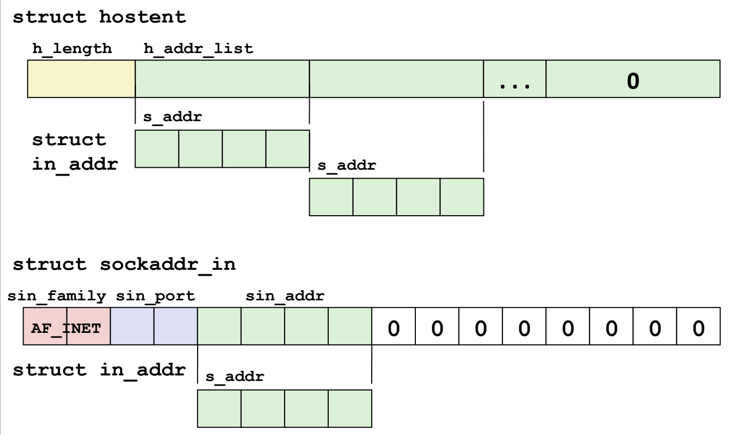
```
/* DNS host entry structure */
struct hostent {
   . . .
   int    h_length;      /* length of an address, in bytes */
   char   **h_addr_list; /* null-terminated array of in_addr structs */
};
```

```
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);
```

Bcopy Argument Data Structures



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;
}
```

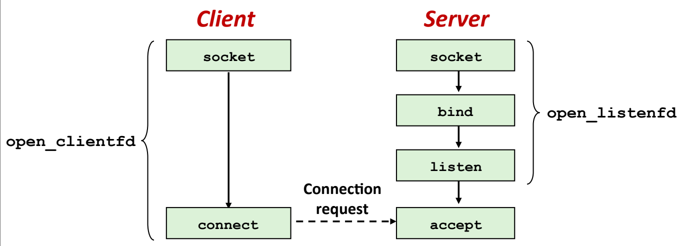
Echo Server: Main Routine

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

    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);
        client_port = ntohs(clientaddr.sin_port);
        printf("server connected to %s (%s), port %u\n",
                hp->h_name, haddrp, client_port);
        echo(connfd);
        Close(connfd);
    }
}
```

Overview of the Sockets Interface



- **Office Telephone Analogy for Server**
  - Socket: Buy a phone
  - Bind: Tell the local administrator what number you want to use
  - Listen: Plug the phone in
  - Accept: Answer the phone when it rings

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;
```

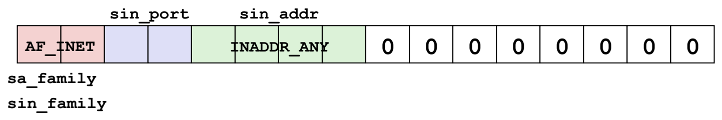
- Handy trick that allows us to rerun the server immediately after we kill it
  - Otherwise we would have to wait about 15 seconds
  - Eliminates "Address already in use" error from `bind()`
- Strongly suggest you do this for all your servers to simplify debugging

Echo Server: `open_listenfd` (initialize socket address)

- Initialize socket with server port number
- Accept connection from any IP address

```
  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
- `LISTENQ` is constant indicating how many pending requests allowed

```
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

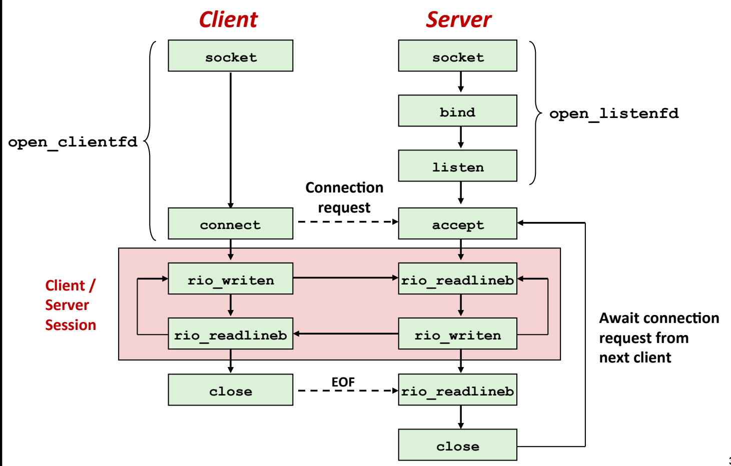
- The server loops endlessly, waiting for connection requests, then reading input from the client, and echoing the input back to the client.

```
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 */
   }
}
```

Overview of the Sockets Interface



Echo Server: `accept`

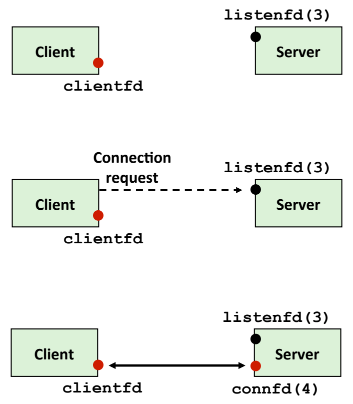
- `accept()` blocks waiting for a connection request

```
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, IP address, and port of the client**

```
struct hostent *hp;  /* pointer to DNS host entry */
char *haddrp;        /* pointer to dotted decimal string */
unsigned short client_port;
hp = Gethostbyaddr((const char *)&clientaddr.sin_addr.s_addr,
                   sizeof(clientaddr.sin_addr.s_addr), AF_INET);
haddrp = inet_ntoa(clientaddr.sin_addr);
client_port = ntohs(clientaddr.sin_port);
printf("server connected to %s (%s), port %u\n",
       hp->h_name, haddrp, client_port);
```

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)`

```
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) {
        upper_case(buf);
        Rio_writen(connfd, buf, n);
        printf("server received %d bytes\n", 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`

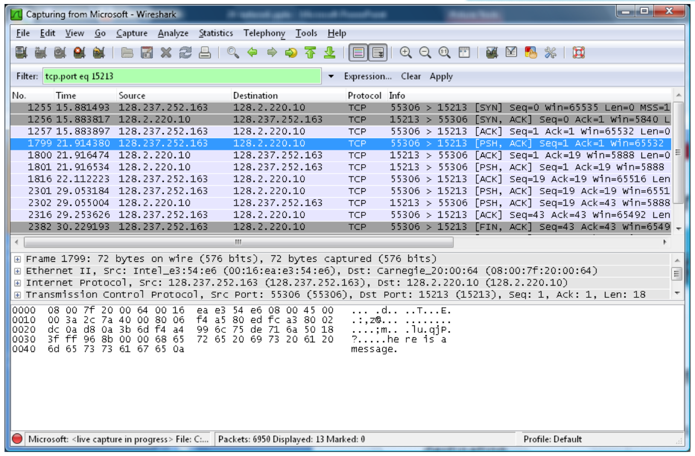
```
greatwhite> echoserver 15213

linux> telnet greatwhite.ics.cs.cmu.edu 15213
Trying 128.2.220.10...
Connected to greatwhite.ics.cs.cmu.edu.
Escape character is '^]'.
hi there
HI THERE
```

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**
  - Updated versions linked to course website
  - Feel free to use this code in your assignments

Watching Echo Client / Server


Capturing from Microsoft - Wireshark
File Edit View Go Capture Analyze Statistics Telephony Tools Help
Filter: tcp.port eq 15213
Expression... Clear Apply

```
No.   Time      Source           Destination      Protocol Info
 1255 15.881493 128.237.252.163  128.2.220.10     TCP      55306 > 15213 [SYN] Seq=0 Win=65535 Len=0 MSS=1
 1256 15.883817 128.2.220.10     128.237.252.163  TCP      15213 > 55306 [SYN, ACK] Seq=0 Ack=1 Win=5840 L
 1257 15.883897 128.237.252.163  128.2.220.10     TCP      55306 > 15213 [ACK] Seq=1 Ack=1 Win=65532 Len=0
 1799 21.914380 128.237.252.163  128.2.220.10     TCP      55306 > 15213 [PSH, ACK] Seq=1 Ack=1 Win=65532
 1800 21.916474 128.2.220.10     128.237.252.163  TCP      15213 > 55306 [ACK] Seq=1 Ack=19 Win=5888 Len=0
 1801 21.916534 128.2.220.10     128.237.252.163  TCP      15213 > 55306 [PSH, ACK] Seq=1 Ack=19 Win=5888
 1816 22.112223 128.237.252.163  128.2.220.10     TCP      55306 > 15213 [ACK] Seq=19 Ack=19 Win=65516 Len
 2301 29.053184 128.237.252.163  128.2.220.10     TCP      55306 > 15213 [PSH, ACK] Seq=19 Ack=19 Win=6551
 2302 29.055004 128.2.220.10     128.237.252.163  TCP      15213 > 55306 [PSH, ACK] Seq=19 Ack=43 Win=5888
 2316 29.253626 128.237.252.163  128.2.220.10     TCP      55306 > 15213 [ACK] Seq=43 Ack=43 Win=65492 Len
 2382 30.229193 128.237.252.163  128.2.220.10     TCP      55306 > 15213 [FIN, ACK] Seq=43 Ack=43 Win=6549

⊞ Frame 1799: 72 bytes on wire (576 bits), 72 bytes captured (576 bits)
⊞ Ethernet II, Src: Intel_e3:54:e6 (00:16:ea:e3:54:e6), Dst: Carnegie_20:00:64 (08:00:7f:20:00:64)
⊞ Internet Protocol, Src: 128.237.252.163 (128.237.252.163), Dst: 128.2.220.10 (128.2.220.10)
⊞ Transmission Control Protocol, Src Port: 55306 (55306), Dst Port: 15213 (15213), Seq: 1, Ack: 1, Len: 18

0000  08 00 7f 20 00 64 00 16  ea e3 54 e6 08 00 45 00   ... .d.. ..T...E.
0010  00 3a 2c 7a 40 00 80 06  f4 a5 80 ed fc a3 80 02   .:,z@... ........
0020  dc 0a d8 0a 3b 6d f4 a4  99 6c 75 de 71 6a 50 18   ....;m.. .lu.qjP.
0030  3f ff 96 8b 00 00 68 65  72 65 20 69 73 20 61 20   ?.....he re is a
0040  6d 65 73 73 61 67 65 0a                            message.

Microsoft: <live capture in progress> File: C:...   Packets: 6950 Displayed: 13 Marked: 0   Profile: Default
```

Ethical Issues

- **Packet Sniffer**
  - Program that records network traffic visible at node
  - Promiscuous mode: Record traffic that does not have this host as source or destination
- **University Policy**

Network Traffic: Network traffic should be considered private. Because of this, any "packet sniffing", or other deliberate attempts to read network information which is not intended for your use will be grounds for loss of network privileges for a period of not less than one full semester. In some cases, the loss of privileges may be permanent. Note that it is permissable to run a packet sniffer explicitly configured in non-promiscuous mode (you may sniff packets going to or from your machine). This allows users to explore aspects of networking while protecting the privacy of others.