CS 105

"Tour of the Black Holes of Computing"

Networking

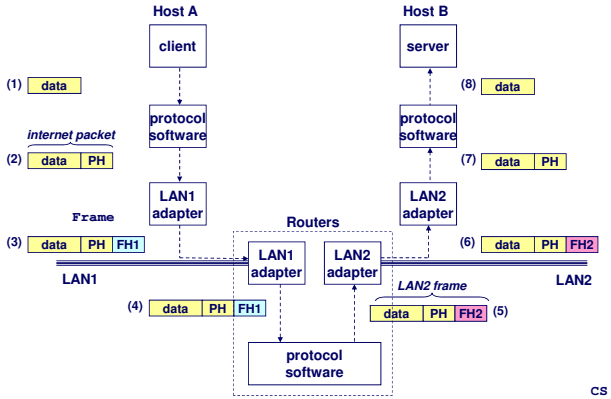
Topics

- Network model
- Client-server programming model
- Sockets interface
- Writing clients and servers

Programmer's View of Internet

1. Hosts are mapped to a set of 32-bit *IP(v4) addresses* or 128-bit *IP(v6) addresses*
   - 134.173.42.100 is Knuth (IPv6: 2620:102:2001:902:f069:3ff:fe3e:8a5c or 2620:102:2001:902::100)
2. IP addresses are mapped to set of identifiers called Internet *domain names*
   - 134.173.42.2 is mapped to www.cs.hmc.edu
   - 128.2.203.164 is mapped to www.cs.cmu.edu
   - Mapping is many-to-many
3. Process on one Internet host can communicate with process on another via a *connection—IP Address, Port Number*

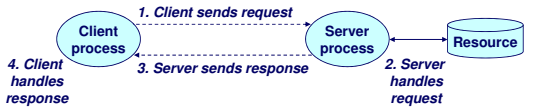
Transferring Data via a Network



Client-Server Transactions

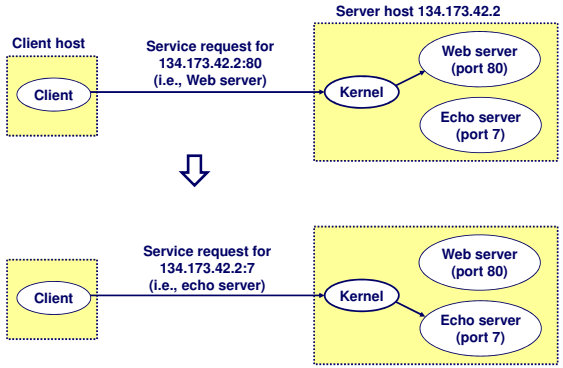
(Almost) every network application is based on client-server model:

- *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)

Using Ports to Identify Services



Sockets Interface

Set of system-level functions used in conjunction with Unix I/O to build network applications.

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

Available on all modern systems

- Unix variants, Windows, OS X, IOS, Android, ARM

Sockets

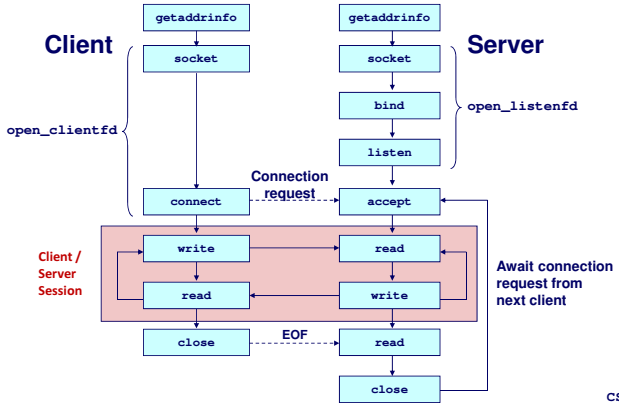
What is a socket?

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

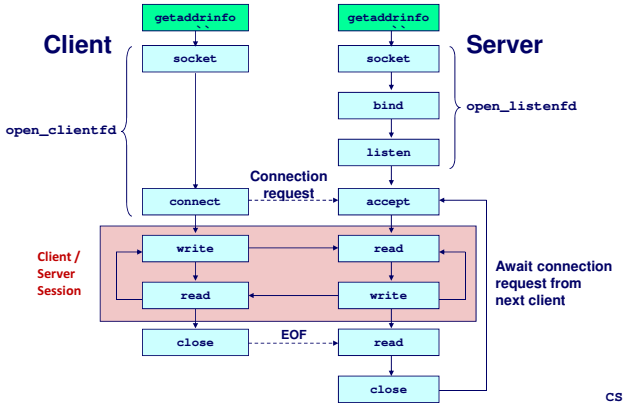
Clients and servers communicate with each other by reading from and writing to socket descriptors

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

Overview of Sockets Interface



Sockets Interface

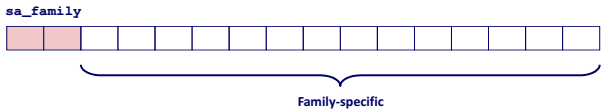


Socket Address Structures

Generic socket address:

- For address arguments to `connect`, `bind`, and `accept`
- Intended to be generic and future-proof
- Too small for IPv6! (Thus, `union` needed; see later)

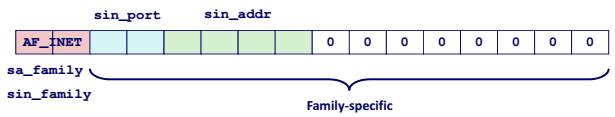
```
struct sockaddr {
  uint16_t  sa_family;    /* Protocol family */
  char      sa_data[14];  /* Address data.  */
};
```



Socket Address Structures

IPv4-specific socket address:

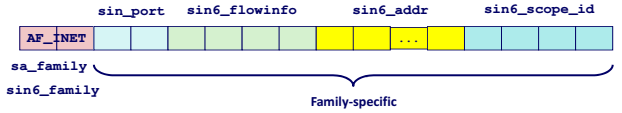
```
struct sockaddr_in  {
  uint16_t        sin_family;  /* Protocol family (always AF_INET) */
  uint16_t        sin_port;    /* Port num in network byte order */
  struct in_addr  sin_addr;    /* IP addr in network byte order */
  unsigned char   sin_zero[8]; /* Pad to sizeof(struct sockaddr) */
};
```



Socket Address Structures

IPv6-specific socket address:

```
struct sockaddr_in6  {
  uint16_t        sin6_family;   /* Protocol family (always AF_INET6) */
  uint16_t        sin6_port;     /* Port num in network byte order */
  uint32_t        sin6_flowinfo; /* IPv6 flow information */
  struct in6_addr sin6_addr;     /* IP addr in network byte order */
  uint32_t        sin6_scope_id; /* scope id (new in RFC2553) */
};
```



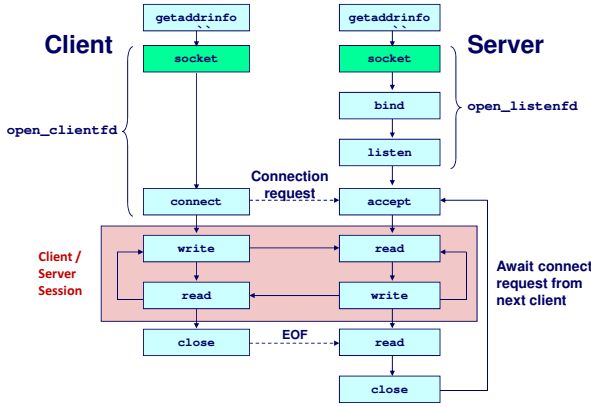
Truly Generic Socket Address Structure

Union that can handle IPv4 or IPv6

- For casting convenience, we adopt the Stevens convention: SA is declared as a generic type that can hold IPv4 or IPV6 socket address
- Must cast (`struct sockaddr_in *`) or (`struct sockaddr_in6 *`) to and from (`SA *`) for functions that take socket-address arguments.

```
typedef union {
    struct sockaddr_in client4;
    struct sockaddr_in6 client6;
} SA;
```


Sockets Interface



Sockets Interface: `socket`

Clients and servers use the `socket` function to create a *socket descriptor*:

```
int socket(int domain, int type, int protocol)
```

Example:

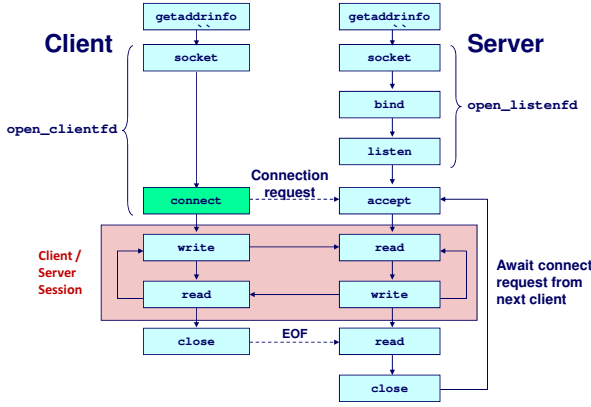
```
int clientfd = Socket(AF_INET6, SOCK_STREAM, 0);
```

Indicates that we are using IPV6 addresses

Indicates that the socket will be the end point of a reliable connection

Protocol-specific! Best practice is to use `getaddrinfo` to generate parameters automatically, so that code is protocol-independent.

Sockets Interface



Sockets Interface: `connect`

A client establishes a connection with a server by calling connect:

```
int connect(int clientfd, SA *addr, socklen_t addrlen);
```

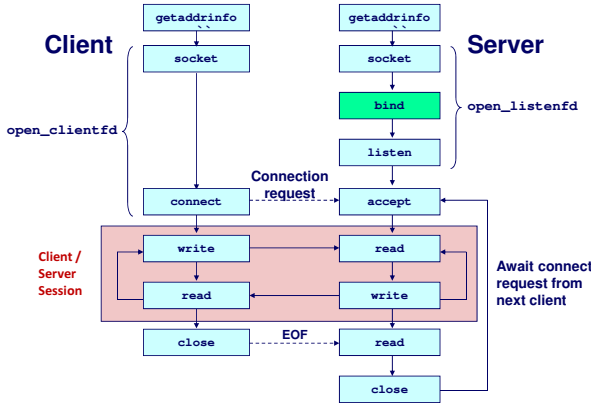
Attempts to establish a connection with server at socket address `addr`

- If successful, then `clientfd` is now ready for reading and writing.
- Resulting connection is characterized by *socket pair*

  `(x:y, addr.sin_addr:addr.sin_port)`
  - `x` is client address
  - `y` is *ephemeral* (temporary) port that uniquely identifies client process on client host

Best practice is to use `getaddrinfo` to supply arguments `addr` and `addrlen`.

Sockets Interface



Sockets Interface: `bind`

Server uses `bind` to ask kernel to associate the server's socket address with a socket descriptor:

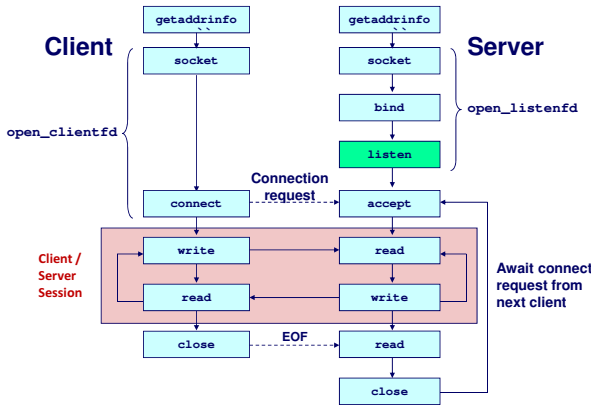
```
int bind(int sockfd, SA *addr, socklen_t addrlen);
```

The process can read bytes that arrive on the connection whose endpoint is `addr` by `read`ing from descriptor `sockfd`.

Similarly, `write`s to `sockfd` are transferred along connection whose endpoint is `addr`.

Again, best practice is to use `getaddrinfo` to supply arguments `addr` and `addrlen`.

Sockets Interface



Sockets Interface: `listen`

By default, kernel assumes that descriptor from socket function is an *active socket* that will be on the client end of a connection

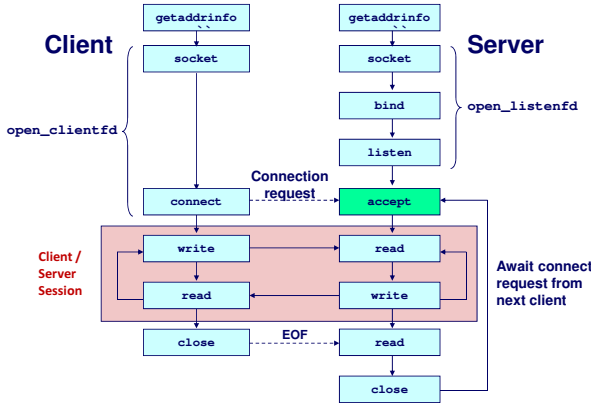
A server calls `listen` to tell kernel that a descriptor will be used by a server rather than a client:

```
int listen(int sockfd, int backlog);
```

Converts `sockfd` from an active socket to a *listening socket* that can accept connection requests from clients

`backlog` is a hint about how many outstanding connection requests the kernel should queue up before starting to refuse requests.

Sockets Interface



Sockets Interface: `accept`

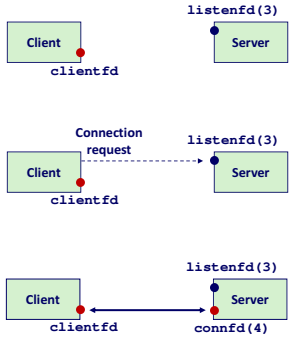
Server waits for connection requests from clients by calling `accept`:

```
int accept(int listenfd, SA *addr, socklen_t *addrlen);
```

Waits for connection request to arrive on connection bound to `listenfd`, then fills in client's socket address in `addr` and size of socket address in `addrlen`

Returns a *connected descriptor* that can be used to communicate with client via Unix I/O routines.

`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

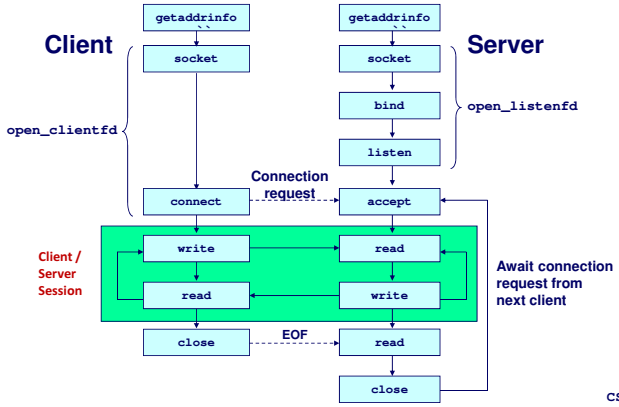
Connected descriptor

- 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 concurrent servers that can communicate over many client connections simultaneously
  - E.g., each time we receive a new request, we fork a child or spawn a thread to handle the request

Sockets Interface



Echo Client Main Routine

```
/* #include lots of stuff */

/* usage: ./echoclient host port */
int main(int argc, char **argv)
{
    int clientfd;
    size_t n;
    char *host, *port, buf[MAXLINE];

    host = argv[1];
    port = argv[2];

    if ((clientfd = open_clientfd(host, port)) == -1)
        exit(1);
    while (fgets(buf, sizeof buf - 1, stdin) != NULL) {
        write(clientfd, buf, strlen(buf));
        n = read(clientfd, buf, sizeof buf - 1);
        if (n != -1) {
            buf[n] = '\0';
            fputs(buf, stdout);
        }
    }
    close(clientfd);
    exit(0);
}
```


Echo Client: `open_clientfd`

```
int open_clientfd(char *hostname, char *port)
{
  int clientfd;
  struct addrinfo hints, *hostaddresses = NULL;

  /* Find out the server's IP address and port */
  memset(&hints, 0, sizeof hints);
  hints.ai_flags = AI_ADDRCONFIG | AI_V4MAPPED;
  hints.ai_family = AF_INET6;
  hints.ai_socktype = SOCK_STREAM;
  if (getaddrinfo(hostname, port, &hints, &hostaddresses) != 0)
    return -1;                          /* Caller must generate error message */
  }

  /* We take advantage of the fact that AF_* and PF_* are identical */
  clientfd = socket(hostaddresses->ai_family, hostaddresses->ai_socktype,
                    hostaddresses->ai_protocol);
  if (clientfd == -1)
    return -1;                          /* check errno for cause of error */
  /* Establish a connection with the server */
  if (connect(clientfd, hostaddresses->ai_addr, hostaddresses->ai_addrlen) == -1)
    return -1;                          /* Caller must generate error message */
  freeaddrinfo(hostaddresses);
  return clientfd;
}
```

This function opens a connection from client to server at `hostname:port` Details follow….

`freeaddrinfo` needed here too (lack of space on slide)

Echo Client: `open_clientfd (getaddrinfo)`

`getaddrinfo` finds out about an Internet host

- `AI_ADDRCONFIG`: only give IPv6 address if our machine can talk IPv6; likewise for IPv4
- `AI_V4MAPPED`: translate IPv6 to IPv4 when needed
- `AF_INET6`: prefer IPv6 to IPv4
- `SOCK_STREAM`: selects a reliable byte-stream connection

```
  hints.ai_flags = AI_ADDRCONFIG | AI_V4MAPPED;
  hints.ai_family = AF_INET6;
  hints.ai_socktype = SOCK_STREAM;
  if (getaddrinfo(hostname, port, &hints, &hostaddresses) != 0)

... (more)
```


Echo Client: `open_clientfd (socket)`

`socket` creates socket descriptor on client

- All details provided by `getaddrinfo`
- Possibility of multiple addresses (serious code must loop & try all)

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

  clientfd = socket(hostaddresses->ai_family, hostaddresses->ai_socktype,
    hostaddresses->ai_protocol);

... (more)
```


Echo Client: `open_clientfd (connect)`

Finally, client creates connection with server

- Client process suspends (blocks) until connection is created
- After resuming, client is ready to begin exchanging messages with server via Unix I/O calls on descriptor `sockfd`
- `hostaddresses` is linked list, must be freed
  - Including on error returns (not shown, for brevity)

```
int clientfd;                   /* socket descriptor */
...
/* Establish a connection with the server */
if (connect(clientfd, hostaddresses->ai_addr, hostaddresses->ai_addrlen) == -1) {
  freeaddrinfo(hostaddresses);
  return -1;
}
freeaddrinfo(hostaddresses);
```


Echo Server: Main Routine

```
int main(int argc, char **argv) {
    int listenfd, connfd, error;
    socklen_t clientlen;
    char * port;
    SA clientaddr;
    char hostname[NI_MAXHOST], hostaddr[NI_MAXHOST];

    listenfd = open_listenfd(argv[1]);
    if (listenfd < 0)
        exit(1);
    while (1) {
        clientlen = sizeof clientaddr;
        connfd = accept(listenfd, (struct sockaddr *)&clientaddr, &clientlen);
        if (connfd == -1)
            continue;                                   /* Needs error message (omitted for space) */
        error = getnameinfo((struct sockaddr*)&clientaddr, clientlen, hostname,
                            sizeof hostname, NULL, 0, 0);
        if (error != 0)
          continue;                                     /* Needs error message (omitted for space) */
        getnameinfo((struct sockaddr*)&clientaddr, clientlen, hostaddr, sizeof hostaddr,
                    NULL, 0, NI_NUMERICHOST);
        printf("server connected to %s (%s)\n", hostname, hostaddr);
        echo(connfd);
        close(connfd);
    }
}
```

This program repeatedly waits for connections, then calls echo(). Details will follow after we look at `open_listenfd()`...

Echo Server: `open_listenfd`

```
int open_listenfd(char *port)
{
    int listenfd, optval = 1, error;
    struct addrinfo hints;
    struct addrinfo *hostaddresses = NULL;

    /* Find out the server's IP address and port */
    memset(&hints, 0, sizeof hints);
    hints.ai_flags = AI_ADDRCONFIG | AI_V4MAPPED | AI_PASSIVE;
    hints.ai_family = AF_INET6;
    hints.ai_socktype = SOCK_STREAM;
    error = getaddrinfo(NULL, port, &hints, &hostaddresses);
    if (error != 0)
        return -1;
    if ((listenfd = socket(hostaddresses->ai_family, hostaddresses->ai_socktype, hostaddresses->ai_protocol)) == -1)
        return -1;  /* Also needs freeaddrinfo but that won't fit on this slide */
    /* Eliminates "Address already in use" error from bind. */
    if (setsockopt(listenfd, SOL_SOCKET, SO_REUSEADDR, (const void *)&optval , sizeof optval) == -1) {
        freeaddrinfo(hostaddresses);
        return -1;
    }
    /* Listenfd will be an endpoint for all requests to port */
    if (bind(listenfd, hostaddresses->ai_addr, hostaddresses->ai_addrlen) == -1)
        return -1; /* Also needs freeaddrinfo but that won't fit on this slide */
    /* Make it a listening socket ready to accept connection requests */
    if (listen(listenfd, LISTEN_MAX) == -1)
        return -1; /* Also needs freeaddrinfo but that won't fit on this slide */
    freeaddrinfo(hostaddresses);
    return listenfd;
}
```

This function opens a file descriptor on which server can *listen* for incoming connections. Details follow…

Echo Server: `open_listenfd` (`getaddrinfo`)

Here, `getaddrinfo` sets up to create generic "port"

- Most options same as for `open_clientfd`
- `AI_PASSIVE`: allow any host to connect to us (because we're a server)
- First argument to `getaddrinfo` is `NULL` because we won't be connecting to a specific host

```
    hints.ai_flags = AI_ADDRCONFIG | AI_V4MAPPED | AI_PASSIVE;
    hints.ai_family = AF_INET6;
    hints.ai_socktype = SOCK_STREAM;
    error = getaddrinfo(NULL, port, &hints, &hostaddresses);
```


Echo Server: `open_listenfd` (`socket`)

`socket` creates socket descriptor on the server

- All important parameters provided by `getaddrinfo`
- Saves us from worrying about IPv4 vs. IPv6

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

/* Create a socket descriptor */
listenfd = socket(hostaddresses->ai_family,
                  hostaddresses->ai_socktype, hostaddresses->ai_protocol);
if (listenfd == -1)
    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 optval) == -1) {
    freeaddrinfo(hostaddresses);
    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 (bind)`

`bind` associates socket with socket address we just created

Again, important parameters come from `getaddrinfo`

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

...
    /* listenfd will be an endpoint for all requests to port
       on any IP address for this host */
    if (bind(listenfd, hostaddresses->ai_addr, hostaddresses->ai_addrlen) == -1) {
        freeaddrinfo(hostaddresses);
        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, LISTEN_MAX) == -1) {
        freeaddrinfo(hostaddresses);
        return -1;
    }
    freeaddrinfo(hostaddresses);
    return listenfd;
}
```

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

Echo Server: Main Loop

Server loops endlessly, waiting for connection requests, then reading input from client and echoing it back to 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 connection request

```
int listenfd; /* listening descriptor */
int connfd;   /* connected descriptor */
SA clientaddr;
socklen_t clientlen;

clientlen = sizeof(clientaddr);
connfd = accept(listenfd, (struct sockaddr *)&clientaddr, &clientlen);
```

SA is union big enough told IPv6 addresses

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

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

`accept` also fills in client's IP address

Echo Server: Identifying Client

Server can determine domain name and IP address of client

```
char hostname[NI_MAXHOST], hostaddr[NI_MAXHOST];
…
    error = getnameinfo((struct sockaddr*)&clientaddr, clientlen,
      hostname, sizeof hostname, NULL, 0, 0);
    if (error != 0) {
      close(connfd);
      continue;
    }
    getnameinfo((struct sockaddr*)&clientaddr, clientlen,
      hostaddr, sizeof hostaddr, NULL, 0, NI_NUMERICHOST);
    printf("server connected to %s (%s)\n", hostname, hostaddr);
```


Echo Server: `echo`

Server uses Unix I/O 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];

    while((n = read(connfd, buf, sizeof buf)) > 0) {
        printf("server received %d bytes\n", n);
        write(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 connection with server running on ***`host`*** and listening on port ***`portnumber`***

Testing Echo Server With `telnet`

```
mallet> ./echoserver 5000
server connected to bow-vpn.cs.hmc.edu (::ffff:192.168.6.5)
server received 5 bytes
server received 8 bytes
```

```
bow> telnet mallet-vpn 5000
Trying 192.168.6.1...
Connected to mallet-vpn.
Escape character is '^]'.
123
123
456789
456789
^]
telnet> quit
Connection closed.
bow>
```

Running Echo Client and Server

```
mallet> echoserver 5000
server connected to bow-vpn.cs.hmc.edu (::ffff:192.168.6.5)
server received 4 bytes
server connected to bow-vpn.cs.hmc.edu (::ffff:192.168.6.5)
server received 7 bytes
...
```

```
bow> echoclient mallet-vpn 5000
123
123
456789
456789
bow>
```


One More Important Function

Real servers often want to handle multiple clients

Problem: you have 3 clients. Only B wants service. You can't really write `serve(A); serve(B); serve(C)` because B must wait for A to ask for service

Solution A: One threads or subprocess per client

Solution B: `select` system call

- Accepts set of file descriptors you're interested in
- Tells you which ones have input waiting or are ready for output
- Then you can read from or write to only the active ones
- For more info, see `man 2 select` and Section 12.2 in text

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

Complete versions of the echo client and server (for IPv4 only) are developed in the text

- Fully general IPv4/IPv6 versions (from these slides) are available from class web page