15-213

"The course that gives CMU its Zip!"

Network programming
Nov 27, 2001

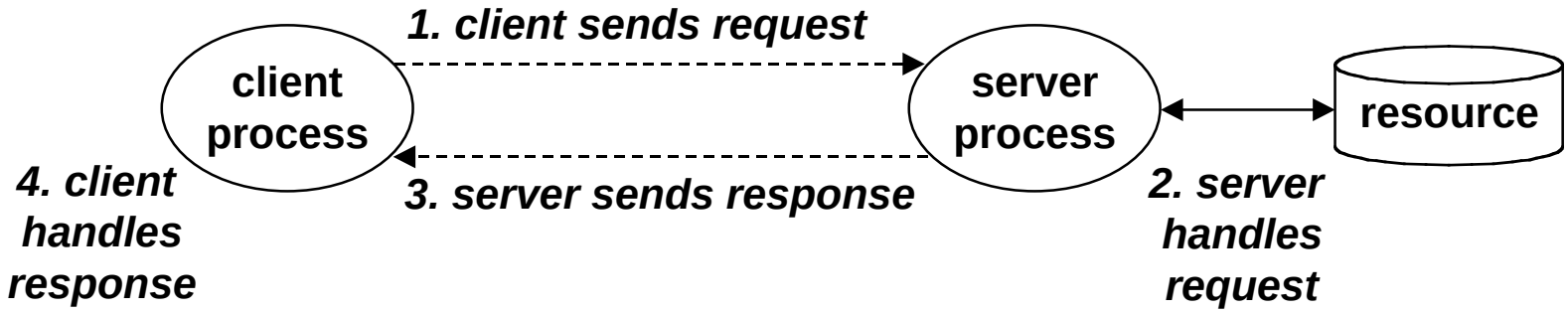
Topics

- Client-server model
- Sockets interface
- Echo client and server

Client-server model

Every network application is based on the client-server model:

- **Application is a *server* process and one or more *client* processes**
- **Server manages some *resource,* and provides *service* by manipulating resource for *clients*.**
- **Client makes a request for a service**
  - **request may involve a conversation according to some server protocol**
- **Server provides service by manipulating the resource on behalf of client and then returning a response**



Clients

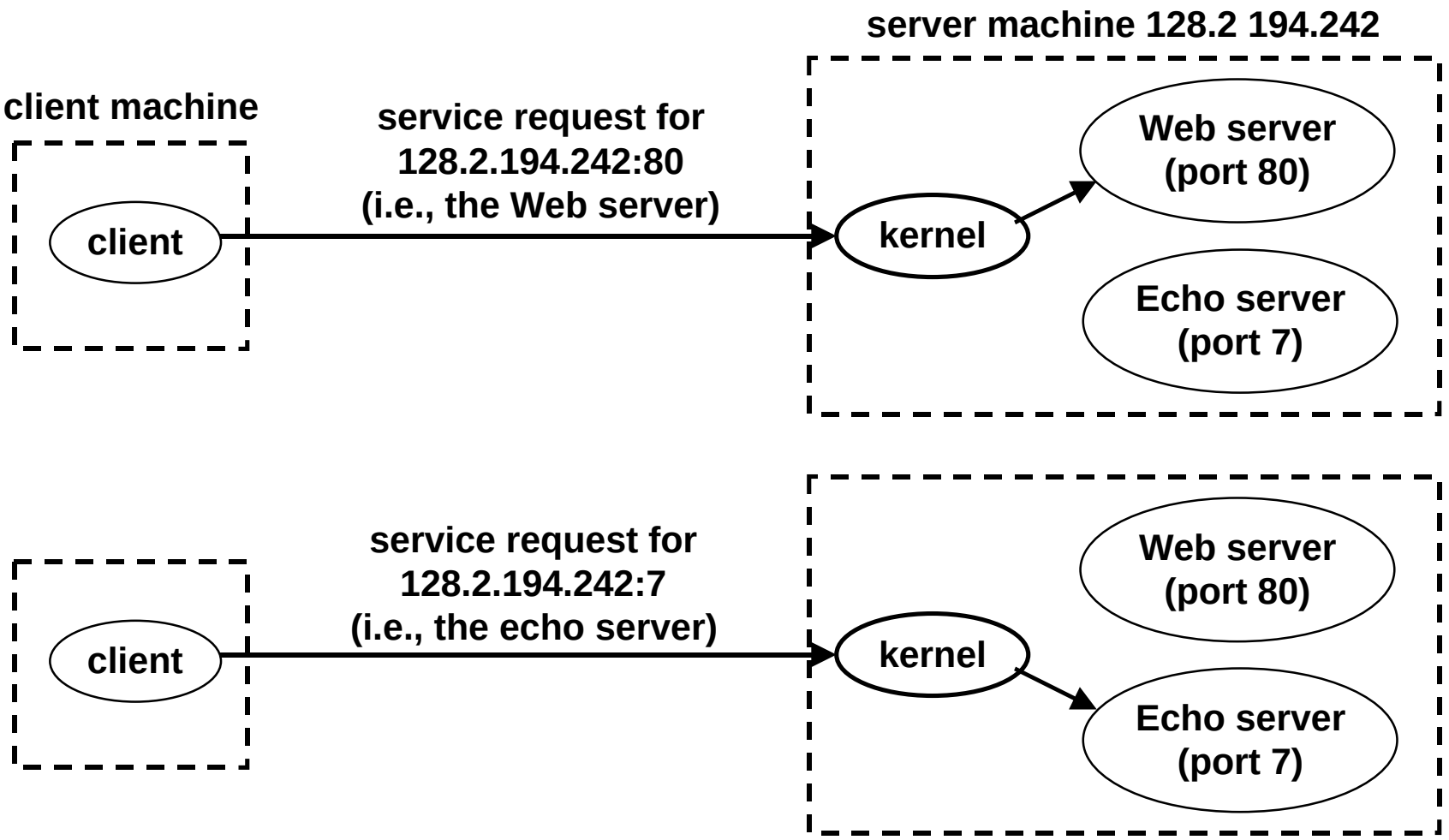
Examples of client programs

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

How does the client find the server?

- The address of the server process has two parts: *IPaddress:port*
  - The *IP address* is a unique 32-bit positive integer that identifies the host (adapter).
    - dotted decimal form: `0x8002C2F2 = 128.2.194.242`
  - The *port* is positive integer associated with a service (and thus a server process) on that machine.
    - port 7: echo 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 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)

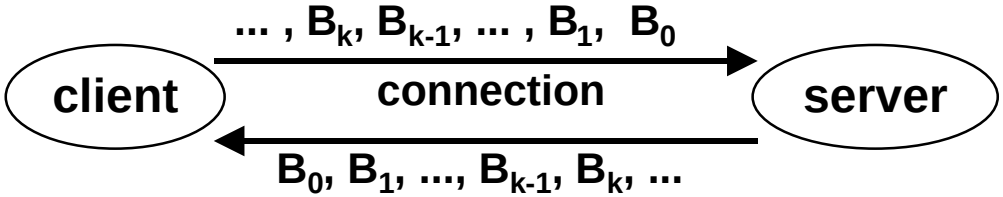
- resource: email “spool” file
- service: stores mail messages in spool file

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

The two basic ways that clients and servers communicate

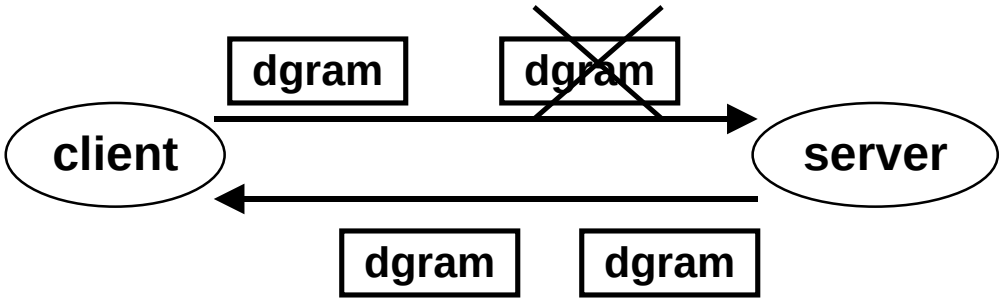
Connections (TCP):

- reliable two-way byte-stream.
- looks like a file.
- akin to placing a phone call.
- slower but more robust.



Datagrams (UDP):

- data transferred in unreliable chunks.
- can be lost or arrive out of order.
- akin to using surface mail.
- faster but less robust.



We will only discuss connections.

Internet connections (review)

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

- **point-to-point, full-duplex, and reliable.**

***A socket* is an endpoint of a connection**

- ***Socket address* is an `IPaddress:port` pair**

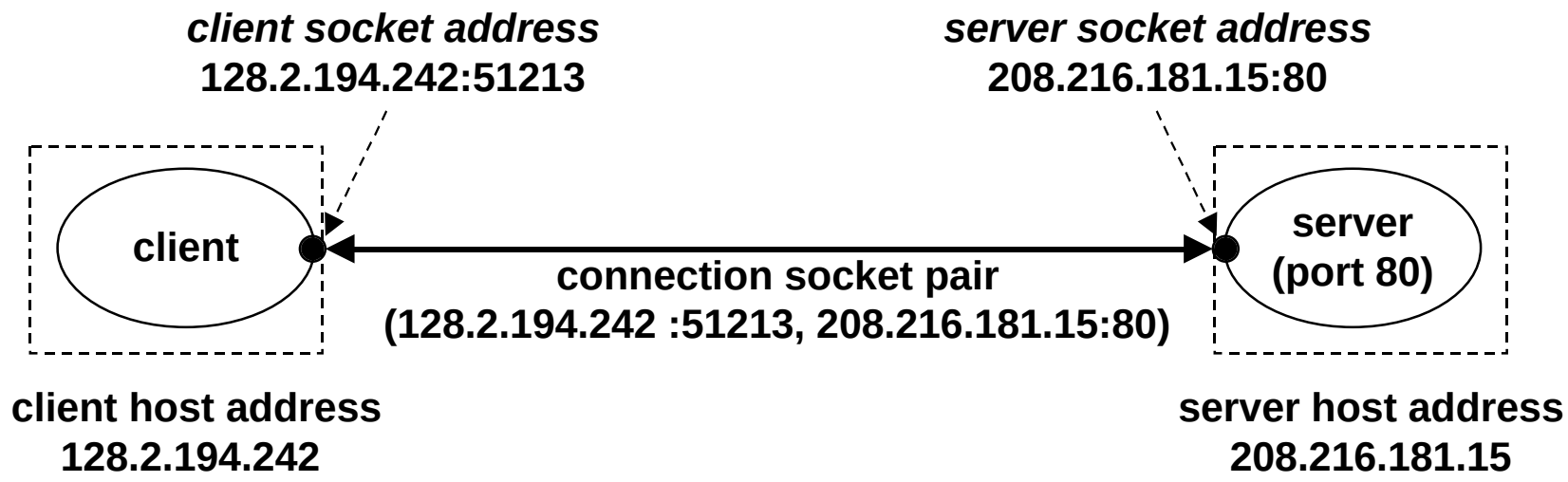
A *port* is a 16-bit integer that identifies a process:

- ***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 (review)



Berkeley 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.

What is a socket?

A *socket* is a descriptor that lets an application read/write from/to the network.

- **Key idea: Unix uses the same abstraction for both file I/O and network I/O.**

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

- **Using regular Unix `read` and `write` I/O functions.**

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

Key data structures

Defined in `/usr/include/netinet/in.h`

```
/* Internet address */
struct in_addr {
  unsigned int s_addr; /* 32-bit IP address */
};

/* Internet style socket address */
struct sockaddr_in  {
  unsigned short int sin_family; /* Address family (AF_INET) */
  unsigned short int sin_port;   /* Port number */
  struct in_addr sin_addr;       /* IP address */
  unsigned char sin_zero[...];   /* Pad to sizeof “struct sockaddr” */
};
```

Internet-style sockets are characterized by a 32-bit IP address and a port.

Key data structures

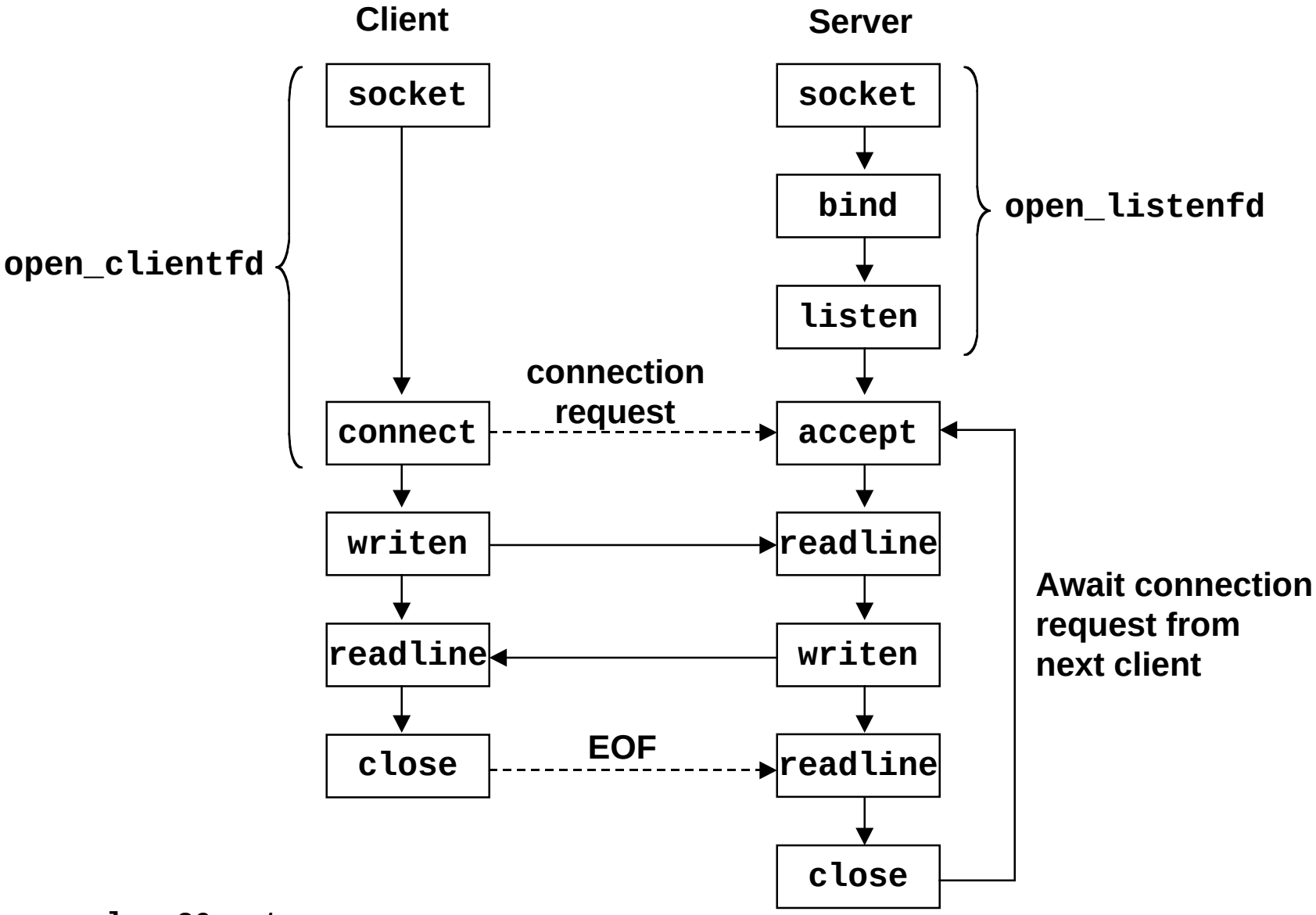
Defined in `/usr/include/netdb.h`

```
/* Domain Name Service (DNS) host entry */
struct hostent {
  char    *h_name;        /* official name of host */
  char    **h_aliases;    /* alias list */
  int     h_addrtype;     /* host address type */
  int     h_length;       /* length of address */
  char    **h_addr_list;  /* list of addresses */
}
```

`hostent` is a DNS host entry that associates a *domain name* (e.g., cmu.edu) with an IP addr (128.2.35.186)

- Can be accessed from user programs
  - `gethostbyname()` [domain name key]
  - `gethostbyaddr()` [IP address key]
- Can also be accessed from the shell using `nslookup` or `dig`.

Overview of the Sockets Interface



Echo client

```
int main(int argc, char **argv)
{
    int clientfd, port;
    char *host, buf[MAXLINE];

    if (argc != 3) {
        fprintf(stderr, "usage: %s <host> <port>\n", argv[0]);
        exit(0);
    }
    host = argv[1];
    port = atoi(argv[2]);

    clientfd = open_clientfd(host, port);
    while (Fgets(buf, MAXLINE, stdin) != NULL) {
        Writen(clientfd, buf, strlen(buf));
        Readline(clientfd, buf, MAXLINE);
        Fputs(buf, stdout);
    }
    Close(clientfd);
}
```

Echo client: open_clientfd()

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

    clientfd = Socket(AF_INET, SOCK_STREAM, 0);

    /* fill in the server's IP address and port */
    hp = Gethostbyname(hostname);
    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 */
    Connect(clientfd, (SA *) &serveraddr, sizeof(serveraddr));

    return clientfd;
}
```

Echo client: `open_clientfd()` (`socket`)

The client creates a socket that will serve as the endpoint of an Internet (AF_INET) connection (SOCK_STREAM).

- `socket()` returns an integer socket descriptor.

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

clientfd = Socket(AF_INET, SOCK_STREAM, 0);
```

Echo client: `open_clientfd()` (`gethostbyname`)

The client builds the server's Internet address.

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

    typedef struct sockaddr SA;    /* generic sockaddr */

...

    /* fill in the server's IP address and port */
    hp = Gethostbyname(hostname);
    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);
```

Echo client: `open_clientfd()` (`connect`)

Then the client creates a connection with the server

- **The client process suspends (blocks) until the connection is created with the server.**
- **At this point the client is ready to begin exchanging messages with the server via Unix I/O calls on the descriptor `sockfd`.**

```
    int clientfd;                       /* socket descriptor */
    struct sockaddr_in serveraddr;      /* server address */

...

    /* establish a connection with the server */
    Connect(clientfd, (SA *) &serveraddr, sizeof(serveraddr));
```

Echo server

```
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;
    int optval;
    struct sockaddr_in serveraddr;

    /* create a socket descriptor */
    listenfd = Socket(AF_INET, SOCK_STREAM, 0);

    /* eliminates "Address already in use" error from bind. */
    optval = 1;
    Setsockopt(listenfd, SOL_SOCKET, SO_REUSEADDR,
               (const void *)&optval , sizeof(int));


... (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);
    Bind(listenfd, (SA *)&serveraddr, sizeof(serveraddr));

    /* make it a listening socket ready to accept
       connection requests */
    Listen(listenfd, LISTENQ);

    return listenfd;
}
```

Echo server: `open_listenfd()` (`socket`)

`socket()` creates a socket descriptor.

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

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

listenfd = Socket(AF_INET, SOCK_STREAM, 0);
```

Echo server: `open_listenfd()` (`setsockopt`)

The socket can be given some attributes.

```
/* eliminates "Address already in use" error from bind. */
optval = 1;
Setsockopt(listenfd, SOL_SOCKET, SO_REUSEADDR,
           (const void *)&optval , sizeof(int));
```

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_addr.s_addr = htonl(INADDR_ANY);
serveraddr.sin_port = htons((unsigned short)port);
```

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

- **`htonl()` converts longs from host byte order to network byte order.**
- **`htons()` convers shorts from host byte order to network 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 */
Bind(listenfd, (SA *)&serveraddr, sizeof(serveraddr));
```

Echo server: `open_listenfd` (`listen`)

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

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

/* make listenf it a server-side listening socket ready to accept
   connection requests from clients */
Listen(listenfd, LISTENQ);
```

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 line from client */
      /* Close(): close the connection */
   }
}
```

Echo server: `accept()`

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

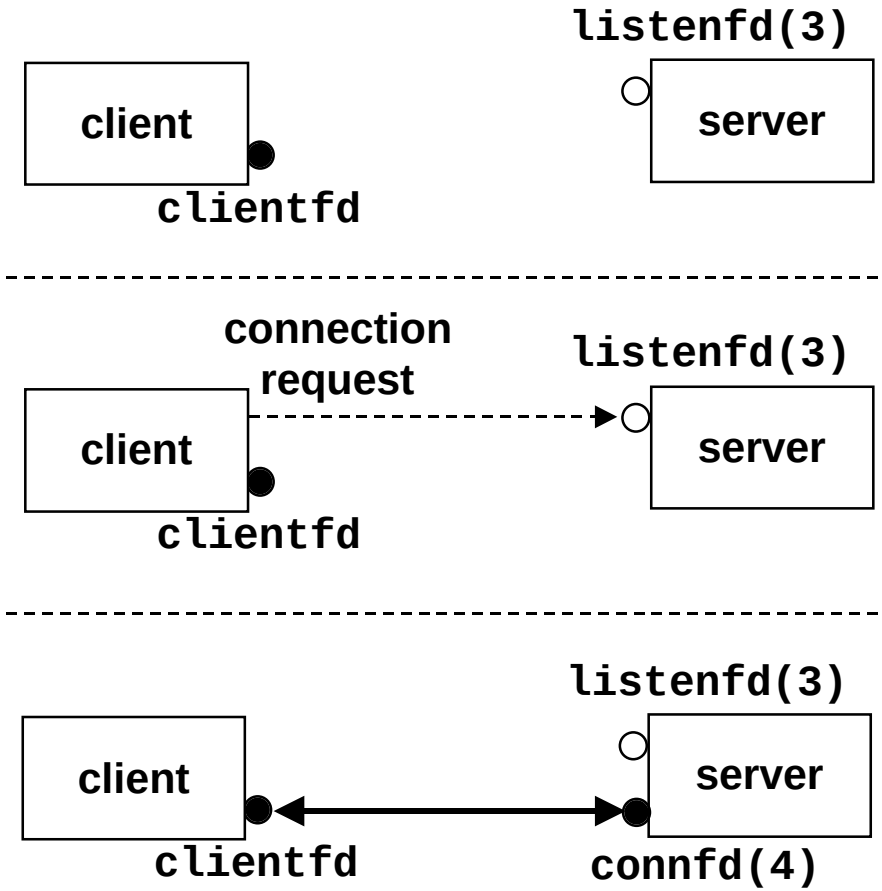
```
int listenfd; /* listening descriptor */
int connfd;   /* connected descriptor */

struct sockaddr_in clientaddr;
int clientlen;

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

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

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

`accept()` also fills in client's address.

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`.

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 Unix I/O to read and echo text lines until EOF (end-of-file) is encountered.

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

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

    while((n = Readline(connfd, buf, MAXLINE)) != 0) {
        printf("server received %d bytes\n", n);
        Writen(connfd, buf, n);
    }
}
```

Testing servers using `telnet`

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

- **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>
```

Running the echo client and 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
...

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>
```

For detailed info

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

- **This is the network programming bible.**

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

- **You should compile and run them for yourselves to see how they work.**
- **Feel free to borrow any of this code.**