Socket Programming

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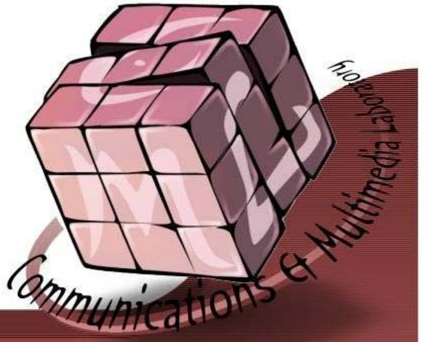

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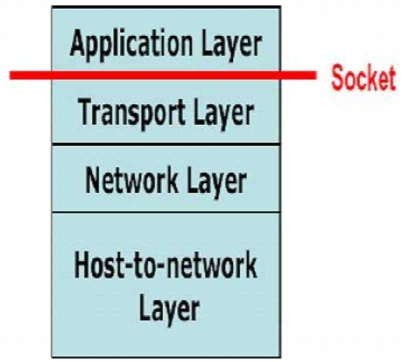
Overview

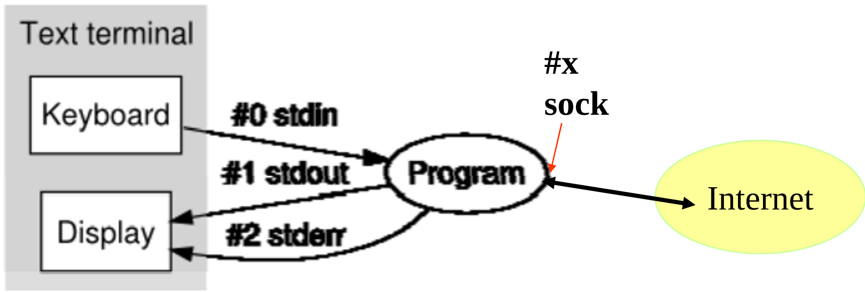
- Background
  - What is Socket?
  - Socket API (Application Programming Interface)
  - TCP (Transmission Control Protocol)
  - UDP (User Datagram Protocol)
- Socket Programming
  - Network Addressing
  - Byte Ordering
  - TCP Server and Client
  - UDP Server and Client

What is Socket?
From the point of view of the networking

- Service access point of TCP/IP protocol stack
  - between Application layer and Transport layer
- A file descriptor that lets an application read/write data from/to the network
- Once configured the application can
  - Send data to the socket
  - Receive data from the socket



What is File Descriptor?

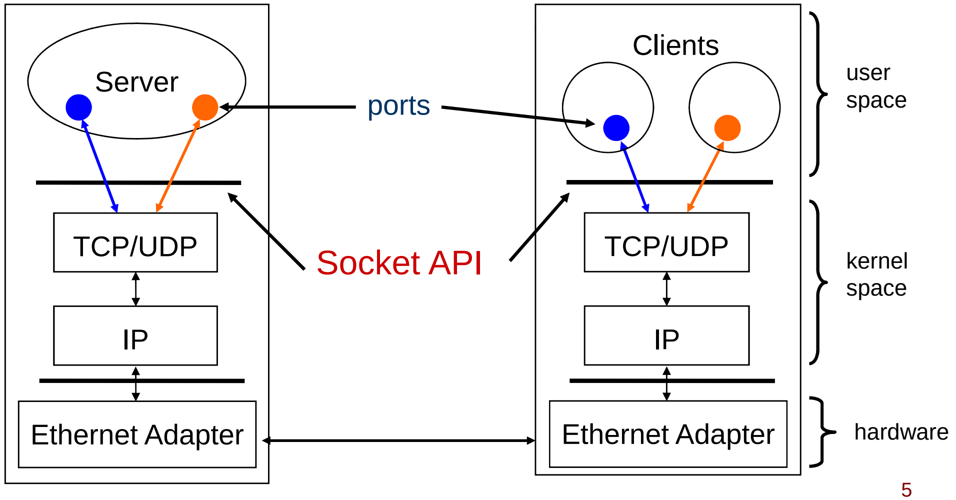


- E.g. cout writes data to stdout (#1)
  cin read data from stdin (#0)

*http://en.wikipedia.org/wiki/File_descriptor

Socket API

Server and Client exchange messages over the network through a common Socket API



User Datagram Protocol (UDP)

UDP

- Single socket to receive messages
- No guarantee of delivery
- Not necessarily in-order delivery
- Datagram – independent packets
- Must address each packet

Postal Mail

- Single mailbox to receive letters
- Unreliable ☺
- Not necessarily in-order delivery
- Letters sent independently
- Must address each reply

Example UDP applications
Multimedia, voice over IP

Transmission Control Protocol (TCP)

TCP

- Reliable – guarantee delivery
- Byte stream – in-order delivery
- Connection-oriented – single socket per connection
- Setup connection followed by data transfer

Telephone Call

- Guaranteed delivery
- In-order delivery
- Connection-oriented
- Setup connection followed by conversation

Example TCP applications
Web, Email, Telnet

TCP vs. UDP

- Transmission Control Protocol (TCP)
  - One-to-one
  - Connection-oriented
  - Reliable
  - In-order delivery
  - Transmission after Connect
- User Datagram Protocol (UDP)
  - One-to-one or one-to many
  - Connectionless
  - Unreliable
  - Unordered delivery
  - Transmission with destination address

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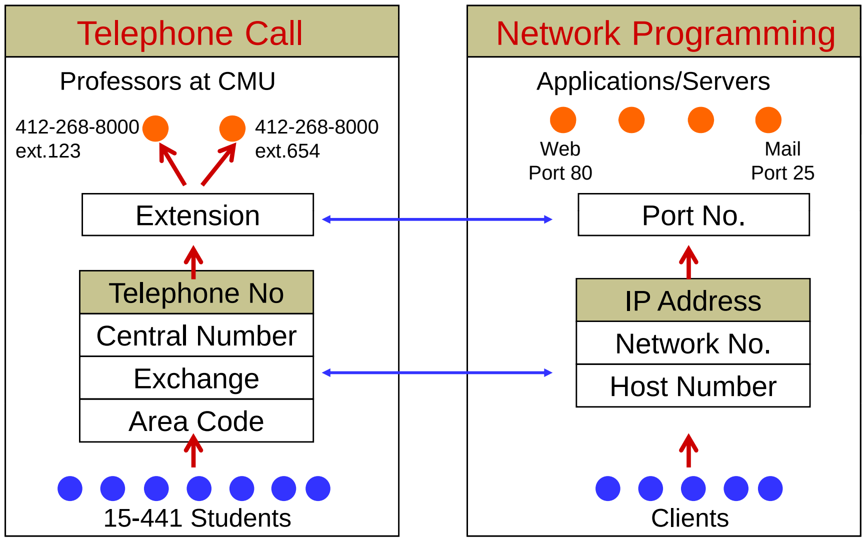
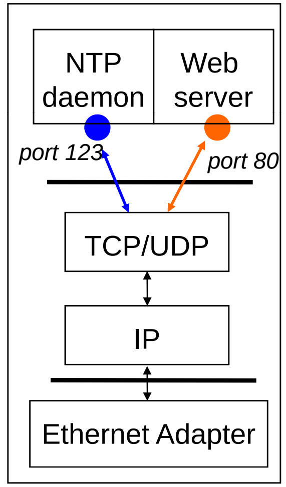
  - Byte Ordering
  - TCP Server and Client
  - UDP Server and Client

Network Addressing Analogy



Concept of Port Numbers

- Port numbers are used to identify “entities” on a host
- Port numbers can be
  - Well-known (port 0-1023)
  - Dynamic or private (port 1024-65535)
- Servers/daemons usually use well-known ports
  - Any client can identify the server/service
  - HTTP = 80, FTP = 21, Telnet = 23, ...
  - /etc/service defines well-known ports
- Clients usually use dynamic ports
  - Assigned by the kernel at run time



Names and Addresses

- Each attachment point on Internet is given unique address
  - Based on location within network – like phone numbers
- Humans prefer to deal with names not addresses
  - DNS provides mapping of name to address
  - Name based on administrative ownership of host

Address Translating Functions

Domain Name	DNS Server *gethostbyname()* →	IP Address (hostent.h_addr.s_addr -> sockaddr_in.sin_addr.s_addr)
Service Name	/etc/service *getservbyname()* →	Port 0~65535 (servent.s_port -> sockaddr_in.s_port)
IP Address (string)	*inet_addr()* →	IP Address (u_long)
IP Address (u_long)	*inet_ntoa()* →	IP Address (string)

Internet Addressing Data Structure

```
#include <netinet/in.h>

/* Internet address structure */
struct in_addr {
        u_long s_addr;          /* 32-bit IPv4 address */
};                              /* network byte ordered */

/* Socket address, Internet style. */
struct sockaddr_in {
      u_char  sin_family;     /* Address Family */
      u_short sin_port;       /* UDP or TCP Port# */
                              /* network byte ordered */
      struct in_addr sin_addr; /* Internet Address */
      char    sin_zero[8];    /* unused */
};
```

- sin_family = AF_INET selects Internet address family

Translating Names to Addresses

- Gethostbyname provides interface to DNS
- Additional useful calls
  - Gethostbyaddr – returns `hostent` given sockaddr_in
  - Getservbyname
    - Used to get service description (typically port number)
    - Returns `servent` based on name

```
#include <netdb.h>

struct hostent *hp; /*ptr to host info for remote*/
struct sockaddr_in peeraddr;
char *name = "www.cs.cmu.edu";

peeraddr.sin_family = AF_INET;
if((hp = gethostbyname(name))!=NULL)
{
        peeraddr.sin_addr.s_addr = ((struct in_addr*)(hp->h_addr))->s_addr;
        printf("Translate %s => %s\n", name, inet_ntoa(peeraddr.sin_addr));
}
```


Dealing with IP Addresses

- IP Addresses are commonly written as strings ("128.2.35.50"), but programs deal with IP addresses as integers.

Converting strings to numerical address:

```
struct sockaddr_in srv;

srv.sin_addr.s_addr = inet_addr("128.2.35.50");
if(srv.sin_addr.s_addr == (in_addr_t) -1) {
      fprintf(stderr, "inet_addr failed!\n"); exit(1);
}
```

Converting a numerical address to a string:

```
struct sockaddr_in srv;
char *t = inet_ntoa(srv.sin_addr);
if(t == 0) {
      fprintf(stderr, "inet_ntoa failed!\n"); exit(1);
}
```

Byte Ordering

```
union {
   u_int32_t addr;  /* 4 bytes address */
   char c[4];
} un;
/* 128.2.194.95 */
un.addr = 0x8002c25f;
/* c[0] = ? */
```

	c[0]	c[1]	c[2]	c[3]
Big Endian	128	2	194	95
Little Endian	95	194	2	128

- Big Endian
  - Sun Solaris, PowerPC, ...
- Little Endian
  - i386, alpha, ...
- Network byte order = Big Endian

Byte Ordering Functions

- Converts between **host byte order** and **network byte order**
  - 'h' = host byte order
  - 'n' = network byte order
  - 'l' = long (4 bytes), converts IP addresses
  - 's' = short (2 bytes), converts port numbers

```
#include <netinet/in.h>

unsigned long int htonl(unsigned long int hostlong);
unsigned short int htons(unsigned short int
hostshort);
unsigned long int ntohl(unsigned long int netlong);
unsigned short int ntohs(unsigned short int
netshort);
```


Recall: What is a Socket?

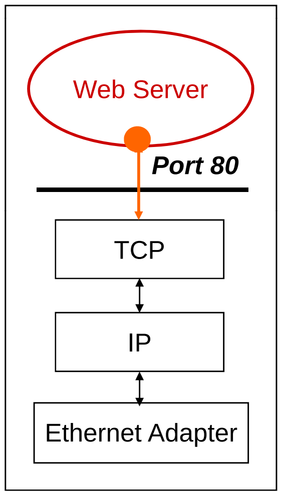
- A socket is a file descriptor that lets an application read/write data from/to the network

```
int fd;          /* socket descriptor */
if ((fd = socket(AF_INET, SOCK_STREAM, 0)) < 0) }
      perror("socket");
      exit(1);
}
```

- ***socket*** returns an integer (socket descriptor)
  - fd < 0 indicates that an error occurred
  - socket descriptors are similar to file descriptors

- AF_INET: associates a socket with the Internet protocol family
- SOCK_STREAM: selects the TCP protocol
- SOCK_DGRAM: selects the UDP protocol

TCP Server



- For example:
  web server

- **What does a *web server* need to do so that a *web client* can connect to it?**

Socket I/O: socket()

- Since web traffic uses TCP, the web server must create a socket of type SOCK_STREAM

```
int fd;           /* socket descriptor */

if((fd = socket(AF_INET, SOCK_STREAM, 0)) < 0) {
      perror("socket");
      exit(1);
}
```

- ***socket*** returns an integer (**socket descriptor**)
  - ***fd*** < 0 indicates that an error occurred
- **AF_INET** associates a socket with the Internet protocol family
- **SOCK_STREAM selects the TCP protocol**

Socket I/O: bind()

- A ***socket*** can be bound to a ***port***

```
int fd;                                 /* socket descriptor */
struct sockaddr_in srv;    /* used by bind() */

/* create the socket */

srv.sin_family = AF_INET; /* use the Internet addr family */

srv.sin_port = htons(80); /* bind socket 'fd' to port 80*/

/* bind: a client may connect to any of my addresses */
srv.sin_addr.s_addr = htonl(INADDR_ANY);

if(bind(fd, (struct sockaddr*) &srv, sizeof(srv)) < 0) {
      perror("bind"); exit(1);
}
```

- **Still not quite ready to communicate with a client...**

Socket I/O: listen()

- ***listen*** indicates that the server will accept a connection

```
int fd;                        /* socket descriptor */
struct sockaddr_in srv;        /* used by bind() */

/* 1) create the socket */
/* 2) bind the socket to a port */

if(listen(fd, 5) < 0) {
      perror("listen");
      exit(1);
}
```

- **Still not quite ready to communicate with a client...**

Socket I/O: accept()

- ***accept*** blocks waiting for a connection

```
int fd;                              /* socket descriptor */
struct sockaddr_in srv;             /* used by bind() */
struct sockaddr_in cli;             /* used by accept() */
int newfd;                          /* returned by accept() */
int cli_len = sizeof(cli); /* used by accept() */

/* 1) create the socket */
/* 2) bind the socket to a port */
/* 3) listen on the socket */

newfd = accept(fd, (struct sockaddr*) &cli, &cli_len);
if(newfd < 0) {
      perror("accept");   exit(1);
}
```

- ***accept*** returns a new socket (***newfd***) with the same properties as the original socket (***fd***)
  - ***newfd*** < 0 indicates that an error occurred

Socket I/O: accept() continued...

```
struct sockaddr_in cli;        /* used by accept() */
int newfd;                     /* returned by accept() */
int cli_len = sizeof(cli);     /* used by accept() */

newfd = accept(fd, (struct sockaddr*) &cli, &cli_len);
if(newfd < 0) {
      perror("accept");
      exit(1);
}
```

- How does the server know which client it is?
  - **cli.sin_addr.s_addr** contains the client’s ***IP address***
  - **cli.sin_port** contains the client’s ***port number***
- Now the server can exchange data with the client by using ***read*** and ***write*** on the descriptor ***newfd***.
- Why does ***accept*** need to return a new descriptor?

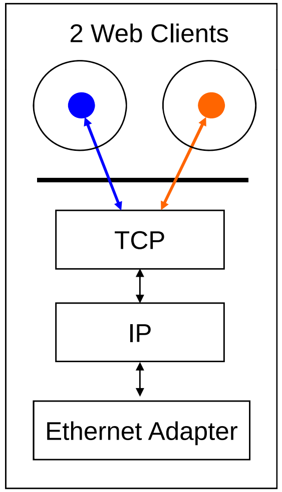
Socket I/O: read()

- ***read*** can be used with a socket
- ***read* <u>blocks</u> waiting for data from the client but does not guarantee that sizeof(buf) is read**

```
int fd;                           /* socket descriptor */
char buf[512];                    /* used by read() */
int nbytes;                      /* used by read() */

/* 1) create the socket */
/* 2) bind the socket to a port */
/* 3) listen on the socket */
/* 4) accept the incoming connection */

if((nbytes = read(newfd, buf, sizeof(buf))) < 0) {
      perror(“read”); exit(1);
}
```


TCP Client

- For example:
  web client



- **How does a *web client* connect to a *web server*?**

Socket I/O: connect()

- ***connect*** allows a client to connect to a server...

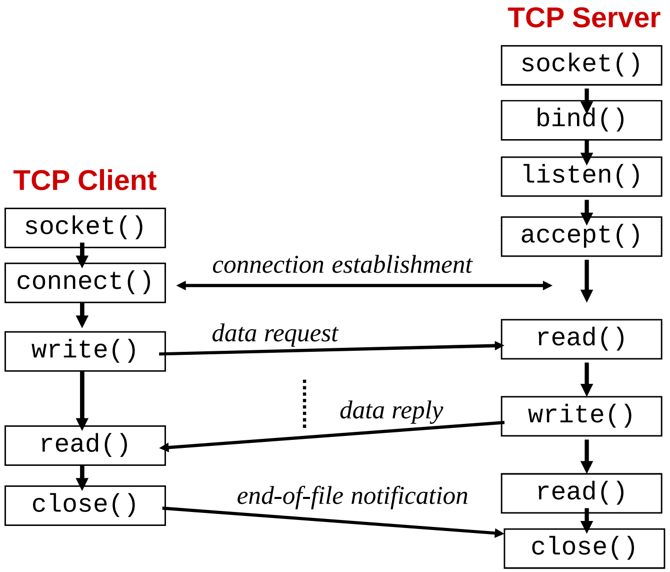
```
int fd;                              /* socket descriptor */
struct sockaddr_in srv;              /* used by connect() */

/* create the socket */

/* connect: use the Internet address family */
srv.sin_family = AF_INET;

/* connect: socket ‘fd’ to port 80 */
srv.sin_port = htons(80);

/* connect: connect to IP Address “128.2.35.50” */
srv.sin_addr.s_addr = inet_addr(“128.2.35.50”);

if(connect(fd, (struct sockaddr*) &srv, sizeof(srv)) < 0) {
      perror(”connect"); exit(1);
}
```

Socket I/O: write()

- ***write*** can be used with a socket

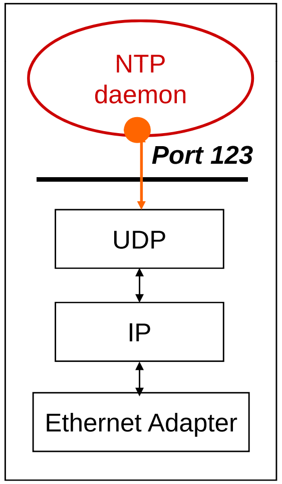
```
int fd;                        /* socket descriptor */
struct sockaddr_in srv;        /* used by connect() */
char buf[512];                 /* used by write() */
int nbytes;                    /* used by write() */

/* 1) create the socket */
/* 2) connect() to the server */

/* Example: A client could “write” a request to a server
*/
if((nbytes = write(fd, buf, sizeof(buf))) < 0) {
      perror(“write”);
      exit(1);
}
```


Review: TCP Client-Server Interaction



from UNIX Network Programming Volume 1, figure 4.1

UDP Server Example



- For example:
  NTP daemon

- **What does a *UDP server* need to do so that a *UDP client* can connect to it?**

Socket I/O: socket()

- The UDP server must create a **datagram** socket…

```
int fd;             /* socket descriptor */

if((fd = socket(AF_INET, SOCK_DGRAM, 0)) < 0) {
      perror(“socket”);
      exit(1);
}
```

- ***socket*** returns an integer (**socket descriptor**)
  - ***fd*** < 0 indicates that an error occurred

- AF_INET: associates a socket with the Internet protocol family
- **SOCK_DGRAM: selects the UDP protocol**

Socket I/O: bind()

- A ***socket*** can be bound to a ***port***

```
int fd;                              /* socket descriptor */
struct sockaddr_in srv;    /* used by bind() */

/* create the socket */

/* bind: use the Internet address family */
srv.sin_family = AF_INET;

/* bind: socket 'fd' to port 80*/
srv.sin_port = htons(80);

/* bind: a client may connect to any of my addresses */
srv.sin_addr.s_addr = htonl(INADDR_ANY);

if(bind(fd, (struct sockaddr*) &srv, sizeof(srv)) < 0) {
       perror("bind"); exit(1);
}
```

- **Now the UDP server is ready to accept packets…**

Socket I/O: recvfrom()

- ***read*** does not provide the client's address to the UDP server

```
int fd;                        /* socket descriptor */
struct sockaddr_in srv;        /* used by bind() */
struct sockaddr_in cli;        /* used by recvfrom() */
char buf[512];                 /* used by recvfrom() */
int cli_len = sizeof(cli);     /* used by recvfrom() */
int nbytes;                    /* used by recvfrom() */

/* 1) create the socket */
/* 2) bind to the socket */

nbytes = recvfrom(fd, buf, sizeof(buf), 0 /* flags */,
               (struct sockaddr*) &cli, &cli_len);
if(nbytes < 0) {
      perror("recvfrom"); exit(1);
}
```

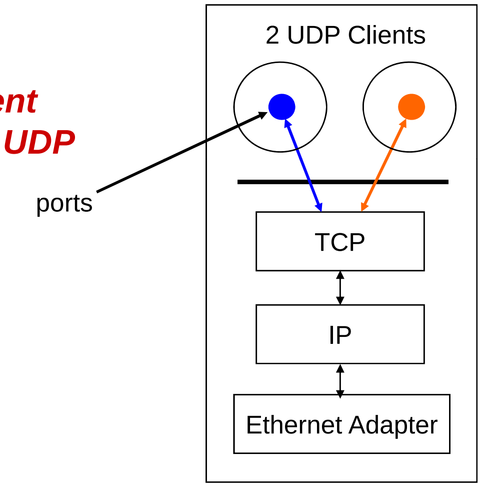

Socket I/O: recvfrom() continued...

```
nbytes = recvfrom(fd, buf, sizeof(buf), 0 /* flags */,
                (struct sockaddr*) cli, &cli_len);
```

- The actions performed by ***recvfrom***
  - returns the number of bytes read (***nbytes***)
  - copies ***nbytes*** of data into ***buf***
  - returns the address of the client (***cli***)
  - returns the length of ***cli*** (***cli_len***)
  - don't worry about flags

UDP Client Example

- **How does a *UDP client* communicate with a *UDP server?***

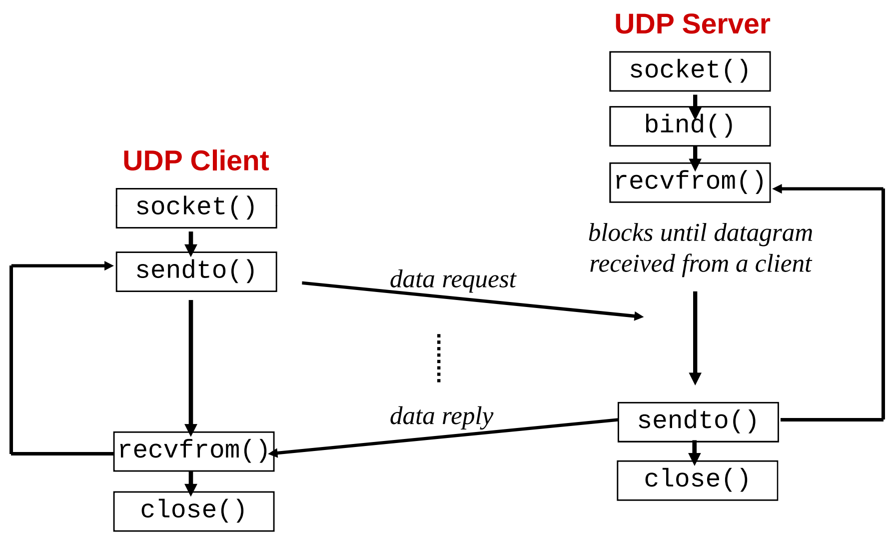


Socket I/O: sendto()

- ***write*** is not allowed
- Notice that the UDP client does not ***bind*** a port number
  - a port number is **dynamically assigned** when the first ***sendto*** is called

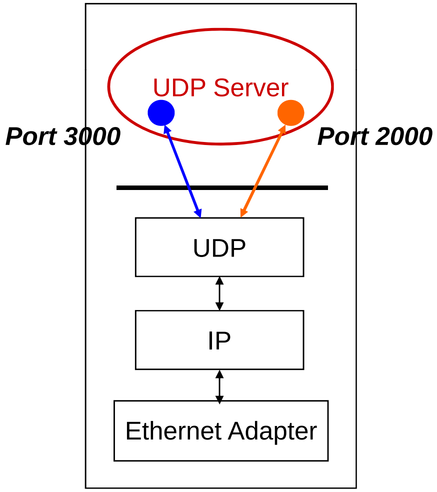
```
int fd;                             /* socket descriptor */
struct sockaddr_in srv;             /* used by sendto() */

/* 1) create the socket */

/* sendto: send data to IP Address “128.2.35.50” port 80 */
srv.sin_family = AF_INET;
srv.sin_port = htons(80);
srv.sin_addr.s_addr = inet_addr(“128.2.35.50”);

nbytes = sendto(fd, buf, sizeof(buf), 0 /* flags */,
                 (struct sockaddr*) &srv, sizeof(srv));
if(nbytes < 0) {
       perror(“sendto”);   exit(1);
}
```


Review: UDP Client-Server Interaction



from UNIX Network Programming Volume 1, figure 8.1

The UDP Server



- **How can the *UDP server* service multiple ports simultaneously?**

UDP Server: Servicing Two Ports

```
int s1;                          /* socket descriptor 1 */
int s2;                          /* socket descriptor 2 */

/* 1) create socket s1 */
/* 2) create socket s2 */
/* 3) bind s1 to port 2000 */
/* 4) bind s2 to port 3000 */

while(1) {
      recvfrom(s1, buf, sizeof(buf), ...);
      /* process buf */

      recvfrom(s2, buf, sizeof(buf), ...);
      /* process buf */
}
```

- **What problems does this code have?**

Socket I/O: select()

```
int select(int maxfds, fd_set *readfds, fd_set *writefds,
           fd_set *exceptfds, struct timeval *timeout);

FD_CLR(int fd, fd_set *fds);   /* clear the bit for fd in fds */
FD_ISSET(int fd, fd_set *fds); /* is the bit for fd in fds? */
FD_SET(int fd, fd_set *fds);   /* turn on the bit for fd in fds */
FD_ZERO(fd_set *fds);          /* clear all bits in fds */
```

- ***maxfds***: number of descriptors to be tested
  - descriptors (0, 1, ... maxfds-1) will be tested
- ***readfds***: a set of *fds* we want to check if data is available
  - returns a set of *fds* ready to read
  - if input argument is *NULL*, not interested in that condition
- ***writefds***: returns a set of *fds* ready to write
- ***exceptfds***: returns a set of *fds* with exception conditions

Socket I/O: select()

```
int select(int maxfds, fd_set *readfds, fd_set *writefds,
           fd_set *exceptfds, struct timeval *timeout);

struct timeval {
      long tv_sec;      /* seconds /
      long tv_usec;           /* microseconds */
}
```

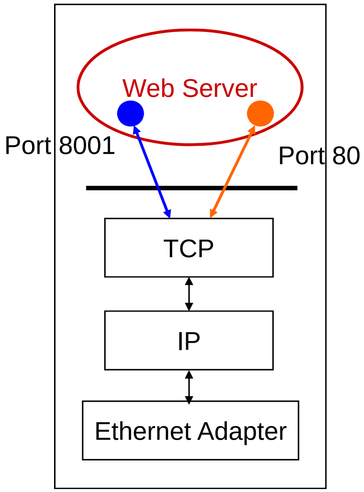
- ***timeout***
  - if NULL, wait forever and return only when one of the descriptors is ready for I/O
  - otherwise, wait up to a fixed amount of time specified by *timeout*
    - if we don't want to wait at all, create a timeout structure with timer value equal to 0
- Refer to the man page for more information

Socket I/O: select()

- ***select*** allows synchronous I/O multiplexing

```
int s1, s2;                   /* socket descriptors */
fd_set readfds;         /* used by select() */

/* create and bind s1 and s2 */
while(1) {
        FD_ZERO(&readfds);            /* initialize the fd set
*/
        FD_SET(s1, &readfds);  /* add s1 to the fd set */
        FD_SET(s2, &readfds);  /* add s2 to the fd set */

        if(select(s2+1, &readfds, 0, 0, 0) < 0) {
                perror("select");
                exit(1);
        }
        if(FD_ISSET(s1, &readfds)) {
                recvfrom(s1, buf, sizeof(buf), ...);
                /* process buf */
        }
        /* do the same for s2 */
}
```


More Details About a Web Server



How can a a *web server* manage multiple connections simultaneously?

Socket I/O: select()

```
int fd, next=0;                                /* original socket */
int newfd[10];                         /* new socket descriptors */
while(1) {
        fd_set readfds;
        FD_ZERO(&readfds); FD_SET(fd, &readfds);

        /* Now use FD_SET to initialize other newfd's
           that have already been returned by accept() */

        select(maxfd+1, &readfds, 0, 0, 0);
        if(FD_ISSET(fd, &readfds)) {
               newfd[next++] = accept(fd, ...);
        }
        /* do the following for each descriptor newfd[n] */
        if(FD_ISSET(newfd[n], &readfds)) {
               read(newfd[n], buf, sizeof(buf));
               /* process data */
        }
}
```

- **Now the web server can support multiple connections...**

Other Solutions for Concurrent Client/Server?

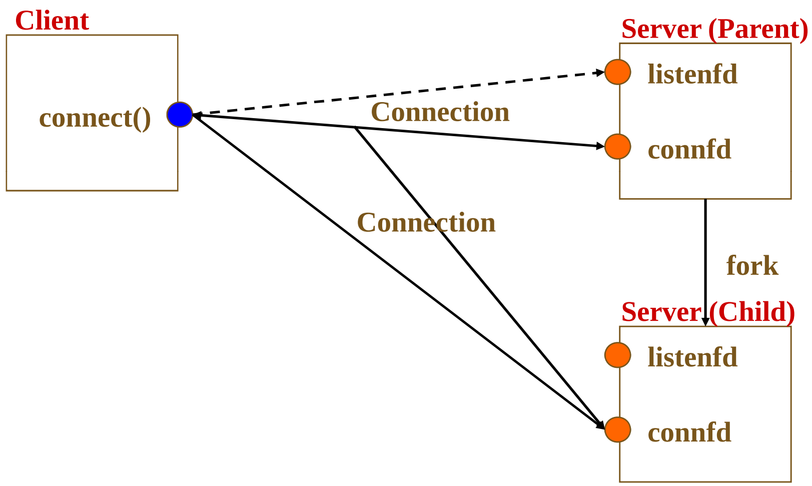
- What we talked above is the single-process concurrent solution, and we still have other choices
- Multi-thread
  - See pthread family manual, e.g. pthread_create()..etc
  - Pthread mutex helps in data synchronizing
    - E.g. pthread_mutex_lock(), pthread_mutex_init()..etc
- Multi-process
  - See fork(), vfork(). If you don't know which one to use, use fork()
  - Share memory for communication between processes
    - E.g. shmget(), shmat(), shmdt()..etc
  - Semaphore to helps in data synchronizing
    - See semaphore in your OS textbook
    - E.g. semget(), semctl(), semop()..etc

E.g. Concurrent Server using fork()

- fork creates a child process.

```
pid_t pid;
int listenfd, connfd;

listenfd = socket(...);
        /* fill in sockaddr_in{} with server's well known port */
bind(listenfd, ...);
listen(listenfd, LISTENQ);

while(1){
        connfd = accept(listenfd, ...); /* probably blocks*/
        if( (pid = fork()) == 0){
                close(listenfd);  /* child closes listening socket*/
                doit(connfd);     /* process the request */
                close(connfd);    /* done with this client */
                exit(0);          /* child terminates */
        }
        close(connfd);            /* parent closes connected socket */
}
```


E.g. Concurrent Server using fork()



Reference

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    - W. Richard Stevens
  - Internetworking with TCP/IP, Vol. III: Client-Server Programming and Applications, Linux/Posix Sockets Version
    - Douglas E. Comer, David L. Stevens, and Michael Evangelista
- man
  - man 2 (socket | bind | listen | read | write | connect | …)
  - man XXXXX
- Google