15-213

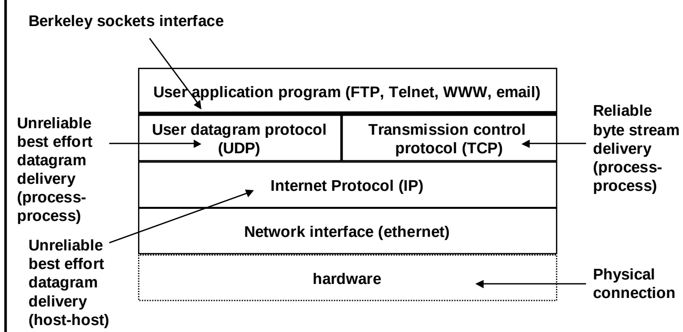
Internetworking II: Network programming

April 20, 2000

Topics

- client/server model
- Berkeley sockets
  - TCP client and server examples
  - UDP client and server examples
- I/O multiplexing with select()

Internet protocol stack



UDP vs TCP

User Datagram Protocol (UDP)

- unreliable datagrams from process to process
- thin veneer over IP
- similar to sending surface mail
  - each message is an independent chunk of data (datagram)
  - messages may not arrive or may arrive out of order
- faster than TCP, requires no server state, but ureliable

Transmission Control Protocol (TCP)

- reliable byte-stream from process to process)
- complex implementation
- similar to placing a phone call
  - no messages, just a continuous stream of bytes over a connection
  - bytes arrive in order
- slower and requires more resources, but cleaner user semantics

Berkeley Sockets Interface

Created in the early 80's as part of the original Berkeley distribution of Unix that contained the TCP/IP protocol stack.

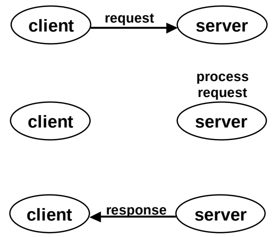
Provides user-level interface to UDP and TCP

Underlying basis for all Internet applications.

Based on client/server programming model

Client/server programming model

- Client + server = distributed computing
- Client & server are both processes
- Server manages a resource
- 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



Internet Servers

- Servers are long-running processes (daemons).
  - Created at boot-time (typically) by the init process
  - Run continuously until the machine is turned off.
- Each server waits for either TCP connection requests or UDP datagrams 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

Server examples (cont)

- DNS name server (53)
  - resource: distributed name database
  - service: distributed database lookup
- Whois server (430)
  - resource: second level domain name database (e.g. cmu.edu)
  - service: database lookup
- Daytime (13)
  - resource: system clock
  - service: retrieves value of system clock
- DHCP server (67)
  - resource: IP addresses
  - service: assigns IP addresses to clients

Server examples (cont)

X server (177)

- resource: display screen and keyboard
- service: paints screen and accepts keyboard input on behalf of a client

AFS file server (7000)

- resource: subset of files in a distributed filesystem (e.g., AFS, NFS)
- service: retrieves and stores files

Kerberos authentication server (750)

- resource: "tickets"
- service: authenticates client and returns tickets

/etc/services file gives a comprehensive list for Linux machines.

File I/O: open()

Must `open()` a file before you can do anything else.

```
int fd;   /* file descriptor */

if ((fd = open("/etc/hosts", O_RDONLY)) < 0) {
   perror("open");
   exit(1);
}
```

`open()` returns a small integer (file descriptor)

- `fd` < 0 indicates that an error occurred

predefined file descriptors:

- 0: stdin
- 1: stdout
- 2: stderr

File I/O: read()

read() allows a program to access the contents of file.

```
char buf[512];
int fd;       /* file descriptor */
int nbytes;   /* number of bytes read */

/* open the file */
/* read up to 512 bytes from file fd */
if ((nbytes = read(fd, buf, sizeof(buf)) < 0) {
   perror("read");
   exit(1);
}
```

`read()` returns the number of bytes read from file `fd`.

- `nbytes` < 0 indicates that an error occurred.

- **if successful, `read()` places `nbytes` bytes into memory starting at address `buf`**

File I/O: write()

`write()` allows a program to modify file contents.

```
char buf[512];
int fd;       /* file descriptor */
int nbytes;   /* number of bytes read */

/* open the file */
/* write up to 512 bytes from buf to file fd */
if ((nbytes = write(fd, buf, sizeof(buf)) < 0) {
   perror("write");
   exit(1);
}
```

`write()` returns the number of bytes written from `buf` to file `fd`.

- `nbytes` < 0 indicates that an error occurred.

What is a socket?

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

- Unix uses the same abstraction for both file I/O and network I/O.

Clients and servers communicate with each other via TCP and UDP using the same socket abstraction.

- applications read and write TCP byte streams by reading from and writing to socket descriptors.
- applications read write UDP datagrams by reading from and writing to socket descriptors.

Main difference between file I/O and socket I/O is how the application "opens" the sock 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)

- DNS is a world-wide distributed database of domain name/IP address mappings.
- Can be accessed from user programs using `gethostbyname()` [domain name to IP address] or `gethostbyaddr()` [IP address to domain name]
- Can also be accessed from the shell using `nslookup` or `dig`.

TCP echo server: prologue

The server listens on a port passed via the command line.

```
/*
 * error - wrapper for perror
 */
void error(char *msg) {
  perror(msg);
  exit(1);
}

int main(int argc, char **argv) {
  /* local variable definitions */

  /*
   * check command line arguments
   */
  if (argc != 2) {
    fprintf(stderr, "usage: %s <port>\n", argv[0]);
    exit(1);
  }
  portno = atoi(argv[1]);
```

TCP echo server: socket()

`socket()` creates a *parent* socket.

```
int parentfd; /* parent socket descriptor */

parentfd = socket(AF_INET, SOCK_STREAM, 0);
  if (parentfd < 0)
    error("ERROR opening socket");
```

socket() returns an integer (socket descriptor)

- **`parentfd` < 0 indicates that an error occurred.**

AF_INET: indicates that the socket is associated with Internet protocols.

SOCK_STREAM: selects the TCP protocol.

TCP echo server: setsockopt()

The socket can be given some attributes.

```
  optval = 1;
  setsockopt(parentfd, SOL_SOCKET, SO_REUSEADDR,
             (const void *)&optval , sizeof(int));
```

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

- **otherwise would have to wait about 15 secs.**
- **eliminates "Address already in use" error.**
- **Suggest you do this for all your servers.**

TCP echo server: init socket address

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

```
  struct sockaddr_in serveraddr; /* server's addr */

  /* this is an Internet address */
  bzero((char *) &serveraddr, sizeof(serveraddr));
  serveraddr.sin_family = AF_INET;

  /* a client can connect to any of my IP addresses */
  serveraddr.sin_addr.s_addr = htonl(INADDR_ANY);

  /* this is the port to associate the socket with */
  serveraddr.sin_port = htons((unsigned short)portno);
```

Binary numbers <u>must</u> be stored in *network byte order* (big-endien)

- **htonl() converts longs from host byte order to network byte order.**
- **htons() convers shorts from host byte order to network byte order.**

TCP echo server: bind()

`bind()` associates the socket with a port.

```
int parentfd;                  /* parent socket */
struct sockaddr_in serveraddr; /* server's addr */


if (bind(parentfd, (struct sockaddr *) &serveraddr,
         sizeof(serveraddr)) < 0)
    error("ERROR on binding");
```

TCP echo server: listen()

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

```
int parentfd;                /* parent socket */

if (listen(parentfd, 5) < 0) /* allow 5 requests to queue up */
    error("ERROR on listen");
```

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

TCP 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 socket */

   while(1) {
      /* accept(): wait for a connection request */
      /* read(): read an input line from the client */
      /* write(): echo the line back to the client */
      /* close(): close the connection */
   }
}
```


TCP echo server: accept()

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

```
int parentfd;  /* parent socket */
int childfd;   /* child socket */
int clientlen; /* byte size of client's address */
struct sockaddr_in clientaddr; /* client addr */

clientlen = sizeof(clientaddr);
childfd = accept(parentfd,
                (struct sockaddr *) &clientaddr, &clientlen);
if (childfd < 0)
   error("ERROR on accept");
```

`accept()` returns a *child* socket descriptor (`childfd`) with the same properties as `parentfd`.

- useful for concurrent servers where the parent forks off a process for each connection request.
- all I/O with the client will be done via the child socket.

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

TCP echo server: identifying client

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

```
struct sockaddr_in clientaddr; /* client addr */
struct hostent *hostp;         /* client DNS host entry */
char *hostaddrp;               /* dotted decimal host addr string */


hostp = gethostbyaddr((const char *)&clientaddr.sin_addr.s_addr,
                        sizeof(clientaddr.sin_addr.s_addr), AF_INET);
if (hostp == NULL)
  error("ERROR on gethostbyaddr");
hostaddrp = inet_ntoa(clientaddr.sin_addr);
if (hostaddrp == NULL)
  error("ERROR on inet_ntoa\n");
printf("server established connection with %s (%s)\n",
          hostp->h_name, hostaddrp);
```

TCP echo server: read()

The server reads an ASCII input line from the client.

```
int childfd;       /* child socket */
char buf[BUFSIZE]; /* message buffer */
int n;             /* message byte size */

bzero(buf, BUFSIZE);
n = read(childfd, buf, BUFSIZE);
if (n < 0)
  error("ERROR reading from socket");
printf("server received %d bytes: %s", n, buf);
```

At this point, it looks just like file I/O.

TCP echo server: write()

Finally, the child echoes the input line back to the client, closes the connection, and loops back to wait for the next connection request.

```
int childfd;       /* child socket */
char buf[BUFSIZE]; /* message buffer */
int n;             /* message byte size */

n = write(childfd, buf, strlen(buf));
if (n < 0)
  error("ERROR writing to socket");

close(childfd);
```


Testing the TCP server with telnet

```
bass> tcpserver 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>
```


TCP client: prologue

The client connects to a host and port passed in on the command line.

```
/*
 * error - wrapper for perror
 */
void error(char *msg) {
    perror(msg);
    exit(0);
}

int main(int argc, char **argv) {
    /* local variable definitions */

    /* check command line arguments */
    if (argc != 3) {
       fprintf(stderr,"usage: %s <hostname> <port>\n", argv[0]);
       exit(0);
    }
    hostname = argv[1];
    portno = atoi(argv[2]);
```

TCP client: socket()

The client creates a socket.

```
int sockfd;  /* socket descriptor */

sockfd = socket(AF_INET, SOCK_STREAM, 0);
if (sockfd < 0)
    error("ERROR opening socket");
```


TCP client: gethostbyname()

The client builds the server's Internet address.

```
struct sockaddr_in serveraddr; /* server address */
struct hostent *server;        /* server DNS host entry */
char *hostname;                /* server domain name */

/* gethostbyname: get the server's DNS entry */
server = gethostbyname(hostname);
if (server == NULL) {
    fprintf(stderr,"ERROR, no such host as %s\n", hostname);
    exit(0);
}

/* build the server's Internet address */
bzero((char *) &serveraddr, sizeof(serveraddr));
serveraddr.sin_family = AF_INET;
bcopy((char *)server->h_addr,
      (char *)&serveraddr.sin_addr.s_addr, server->h_length);
serveraddr.sin_port = htons(portno);
```


TCP client: connect()

Then the client creates a connection with the server.

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

if (connect(sockfd, &serveraddr, sizeof(serveraddr)) < 0)
      error("ERROR connecting");
```

At this point the client is ready to begin exchanging messages with the server via `sockfd`

- **notice that there is no notion of a parent and child socket on a client.**

TCP client: read(), write(), close()

The client reads a message from stdin, sends it to the server, waits for the echo, and terminates.

```
    /* get message line from the user */
    printf("Please enter msg: ");
    bzero(buf, BUFSIZE);
    fgets(buf, BUFSIZE, stdin);

    /* send the message line to the server */
    n = write(sockfd, buf, strlen(buf));
    if (n < 0)
      error("ERROR writing to socket");

    /* print the server's reply */
    bzero(buf, BUFSIZE);
    n = read(sockfd, buf, BUFSIZE);
    if (n < 0)
      error("ERROR reading from socket");
    printf("Echo from server: %s", buf);
    close(sockfd);
    return 0;
```

Running the TCP client and server

```
bass> tcpserver 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> tcpclient bass 5000
Please enter msg: 123
Echo from server: 123
kittyhawk> tcpclient bass 5000
Please enter msg: 456789
Echo from server: 456789
kittyhawk>
```


UDP echo server: socket(), bind()

Identical to TCP server, except for creating a socket of type SOCK_DGRAM

```
sockfd = socket(AF_INET, SOCK_DGRAM, 0);
if (sockfd < 0)
   error("ERROR opening socket");

optval = 1;
setsockopt(sockfd, SOL_SOCKET, SO_REUSEADDR,
           (const void *)&optval , sizeof(int));

bzero((char *) &serveraddr, sizeof(serveraddr));
serveraddr.sin_family = AF_INET;
serveraddr.sin_addr.s_addr = htonl(INADDR_ANY);
serveraddr.sin_port = htons((unsigned short)portno);

if (bind(sockfd, (struct sockaddr *) &serveraddr,
        sizeof(serveraddr)) < 0)
  error("ERROR on binding");
```


UDP echo server: main loop

```
main() {

   /* create and configure the UDP socket */

   while(1) {
      /* recvfrom(): read a UDP datagram */
      /* sendto(): echo datagram back to the client */
   }
}
```


UDP server: recvfrom(), sendto()

The main server loop is a simple sequence of receiving and sending datagrams.

```
clientlen = sizeof(clientaddr);
while (1) {

   bzero(buf, BUFSIZE);
   n = recvfrom(sockfd, buf, BUFSIZE, 0,
                (struct sockaddr *) &clientaddr, &clientlen);
   if (n < 0)
      error("ERROR in recvfrom");

   n = sendto(sockfd, buf, strlen(buf), 0,
              (struct sockaddr *) &clientaddr, clientlen);
   if (n < 0)
      error("ERROR in sendto");
}
```

Much simpler than the TCP server:

- no accept(), no distinction between child and parent sockets.
- however, user must develop logic for lost or misordered datagrams.

UDP client: socket(), gethostbyname()

Identical to TCP client, except for SOCK_DGRAM.

```
/* socket: create the socket */
   sockfd = socket(AF_INET, SOCK_DGRAM, 0);
   if (sockfd < 0)
       error("ERROR opening socket");

   /* gethostbyname: get the server's DNS entry */
   server = gethostbyname(hostname);
   if (server == NULL) {
       fprintf(stderr,"ERROR, no such host as %s\n", hostname);
       exit(0);
   }

   /* build the server's Internet address */
   bzero((char *) &serveraddr, sizeof(serveraddr));
   serveraddr.sin_family = AF_INET;
   bcopy((char *)server->h_addr,
         (char *)&serveraddr.sin_addr.s_addr, server->h_length);
   serveraddr.sin_port = htons(portno);
```


UDP client: sendto(), recvfrom()

The client sends a datagram to the server, waits for the echo, and terminates.

```
/* get a message from the user */
bzero(buf, BUFSIZE);
printf("Please enter msg: ");
fgets(buf, BUFSIZE, stdin);

/* send the message to the server */
serverlen = sizeof(serveraddr);
n = sendto(sockfd, buf, strlen(buf), 0, &serveraddr, serverlen);
if (n < 0)
  error("ERROR in sendto");

/* print the server's reply */
n = recvfrom(sockfd, buf, strlen(buf), 0, &serveraddr, &serverlen);
if (n < 0)
  error("ERROR in recvfrom");
printf("Echo from server: %s", buf);
return 0;
```


Multiplexing I/O: select()

How does a server manage multiple file and socket descriptors?

Example: a TCP server that also accepts user commands from stdin.

- "c": print the number of connection requests so far
- "q": terminate the server

Problem:

- I/O events can occur asynchronously
- input is available on stdin
  - e.g., user has typed a line and hit return
- connection request is outstanding on parentfd
- blocking in either fgets() or accept() would create an unresponsive server.

Solution:

- select() system call

TCP server based on select()

Use `select()` to detect events without blocking.

```
/*
 * main loop: wait for connection request or stdin command.
 * If connection request, then echo input line
 * and close connection. If command, then process.
 */
 printf("server> ");
 fflush(stdout);

 while (notdone) {
    /*
     * select: check if the user typed something to stdin or
     * if a connection request arrived.
     */
    FD_ZERO(&readfds);          /* initialize the fd set */
    FD_SET(parentfd, &readfds); /* add socket fd */
    FD_SET(0, &readfds);        /* add stdin fd (0) */
    if (select(parentfd+1, &readfds, 0, 0, 0) < 0) {
      error("ERROR in select");
    }
    ...
```

TCP server based on select()

First we check for a pending event on stdin.

```
/* if the user has typed a command, process it */
if (FD_ISSET(0, &readfds)) {
   fgets(buf, BUFSIZE, stdin);
   switch (buf[0]) {
   case 'c': /* print the connection count */
      printf("Received %d conn. requests so far.\n", connectcnt);
      printf("server> ");
      fflush(stdout);
      break;
   case 'q': /* terminate the server */
      notdone = 0;
      break;
   default: /* bad input */
      printf("ERROR: unknown command\n");
      printf("server> ");
      fflush(stdout);
   }
}
```


TCP server based on select()

Next we check for a pending connection request.

```
/* if a connection request has arrived, process it */
if (FD_ISSET(parentfd, &readfds)) {
   childfd = accept(parentfd,
                    (struct sockaddr *) &clientaddr, &clientlen);
   if (childfd < 0)
      error("ERROR on accept");
   connectcnt++;

   bzero(buf, BUFSIZE);
   n = read(childfd, buf, BUFSIZE);
   if (n < 0)
      error("ERROR reading from socket");

   n = write(childfd, buf, strlen(buf));
   if (n < 0)
      error("ERROR writing to socket");
   close(childfd);
}
```


For more info

Complete versions of the clients and servers are available from the course web page.

- **follow the “Lectures” link.**

You should compile and run them for yourselves to see how they work.