15-441

Network Programming
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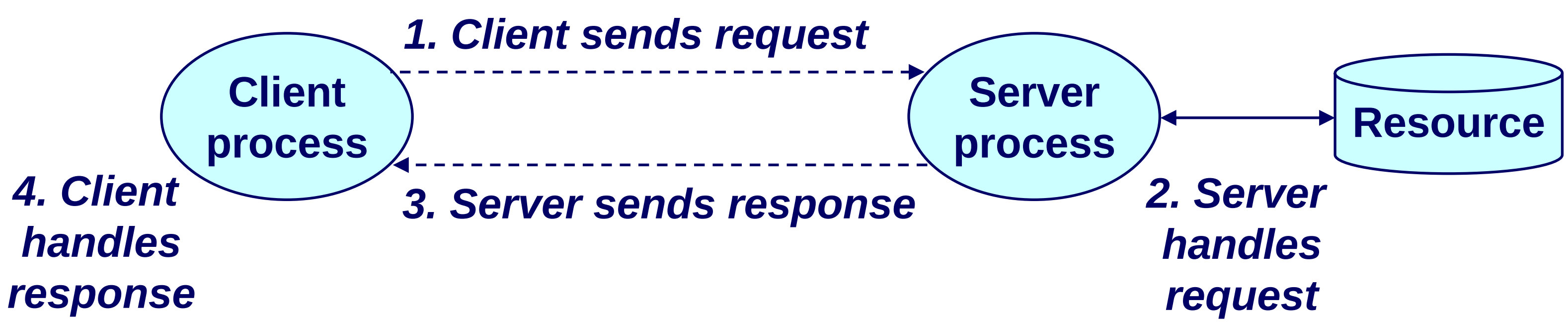
Slides based on those of Dave Maltz, Randy Bryant, Geoff Langale, and the 15-213 crew

Topics

- Programmer's view of the Internet
- Sockets interface
- Writing clients and servers
- Concurrency with I/O multiplexing
- Debugging With GDB
- Version Control (RCS/CVS)
- Tips from the trenches: Projects 1 & 2

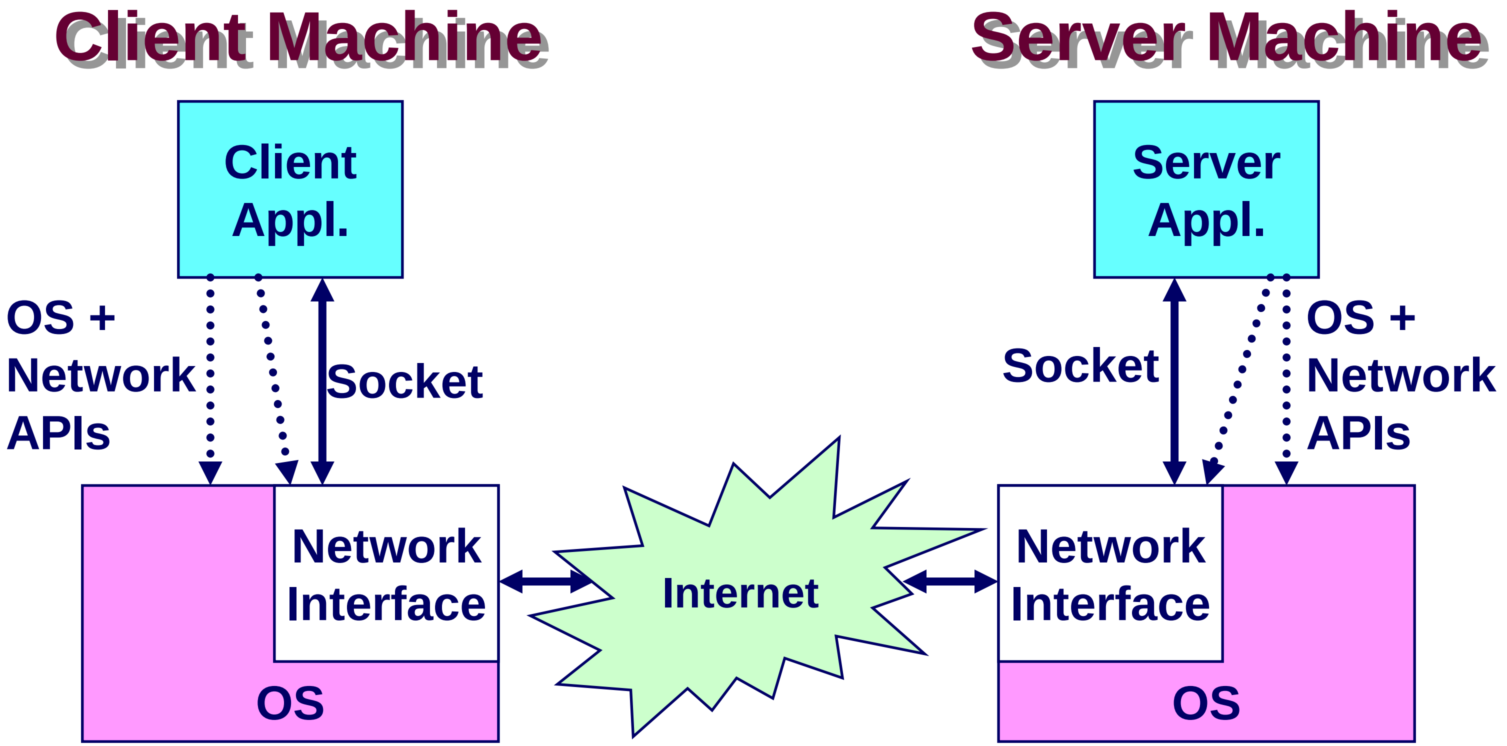
A Client-Server Exchange

- A ***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).

Network Applications



Access to Network via Program Interface

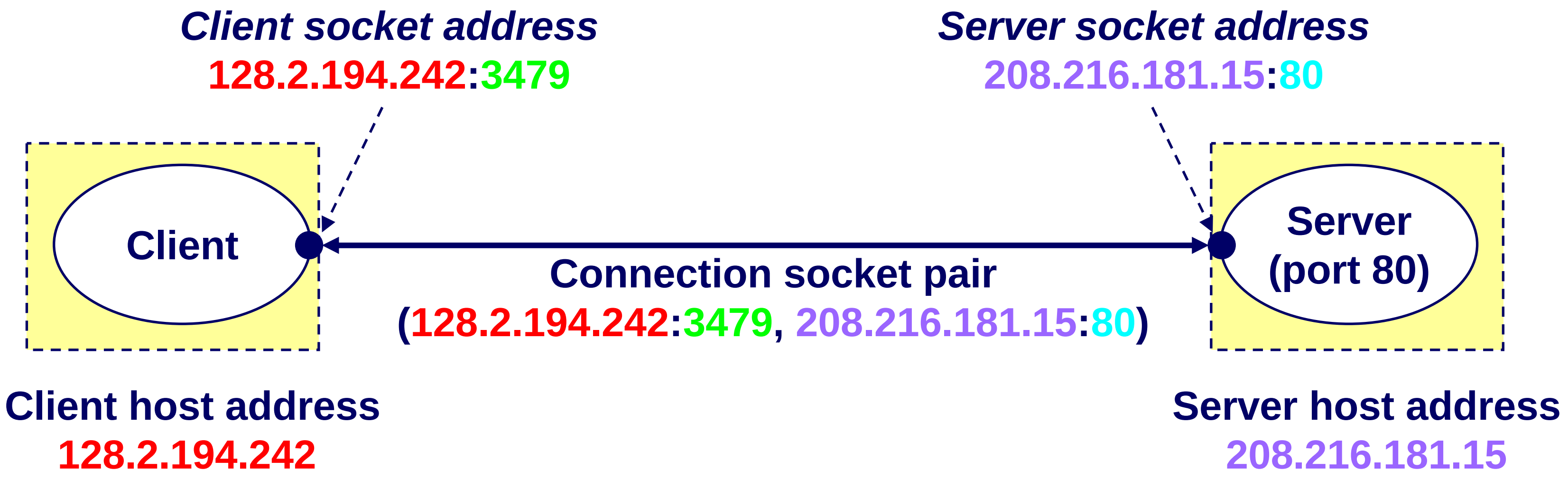
- Sockets make network I/O look like files
- Call system functions to control and communicate
- Network code handles issues of routing, segmentation.

Internet Connections (TCP/IP)

Two common paradigms for clients and servers communication

- **Datagrams (UDP protocol SOCK_DGRAM)**
- **Connections (TCP protocol, SOCK_STREAM)**

Connections are point-to-point, full-duplex (2-way communication), and reliable. (TODAY'S TOPIC!)



Note: 3479 is an ephemeral port allocated by the kernel

Note: 80 is a well-known port associated with Web servers

Clients

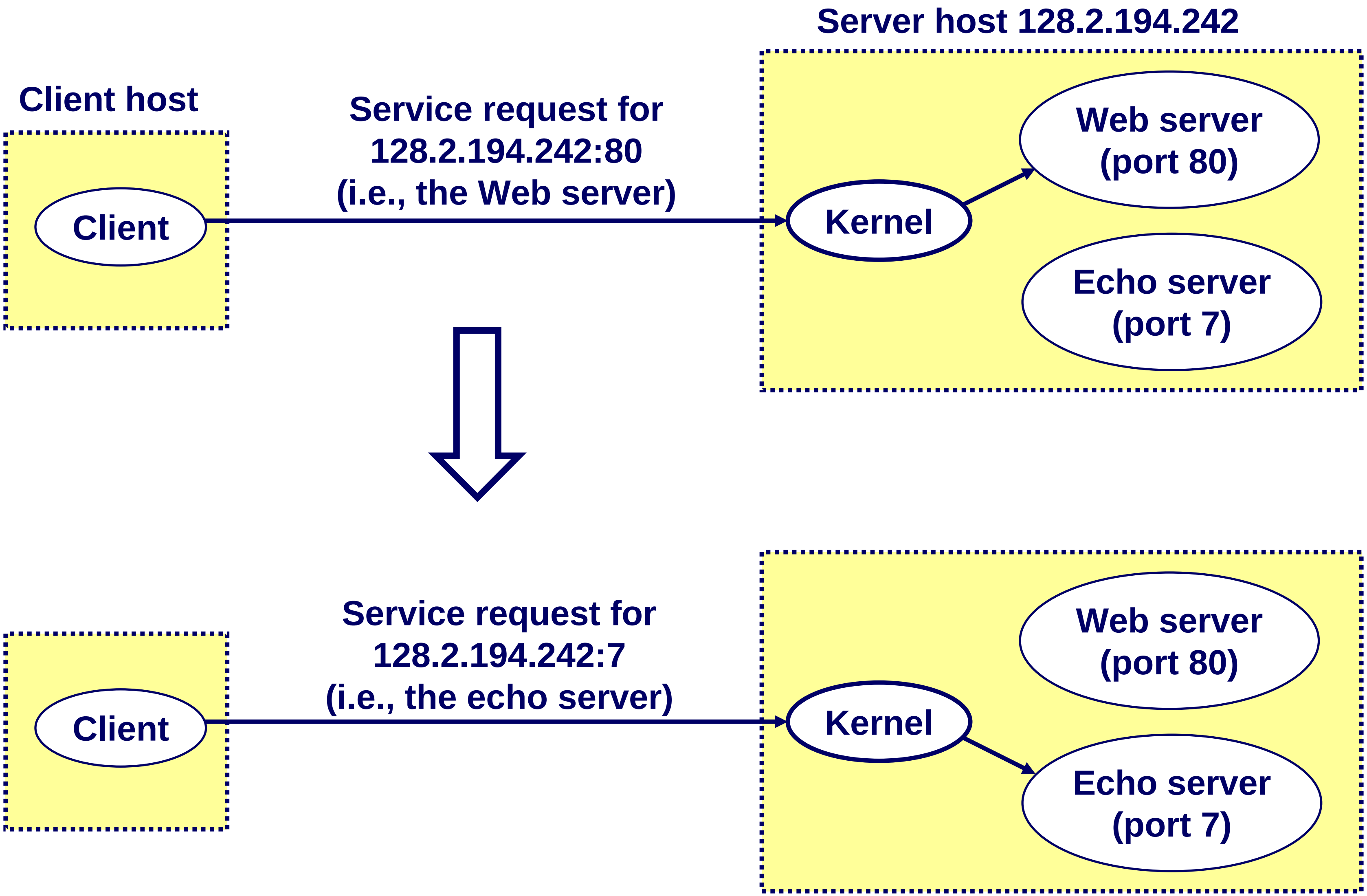
Examples of client programs

- **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 adaptor 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 known ports**
  - **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.**

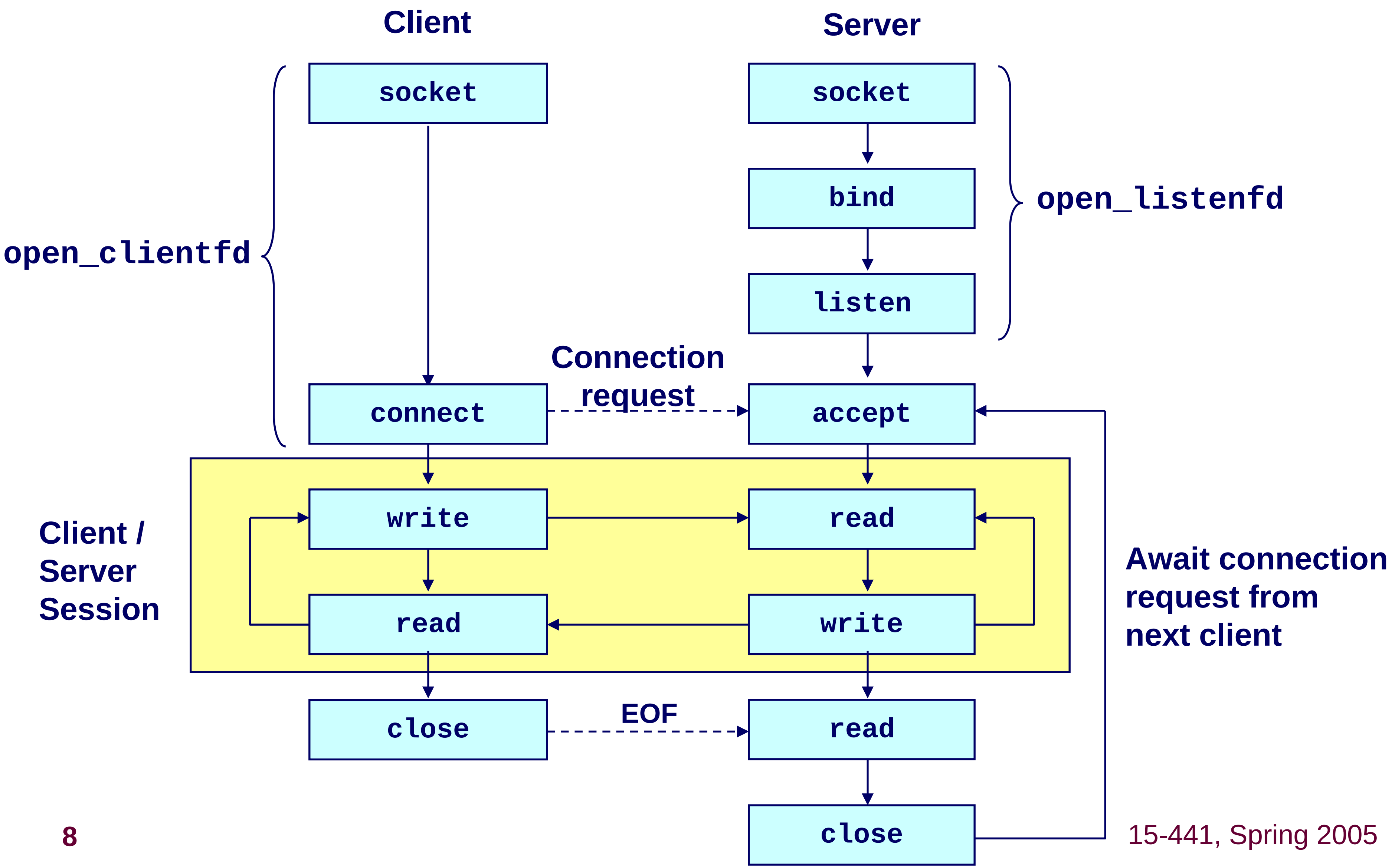
Each server waits for requests to arrive on a well-known port associated with a particular service.

- **Port 7: echo server**
- **Port 23: telnet server**
- **Port 25: mail server**
- **Port 80: HTTP server**

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

A machine that runs a server process is also often referred to as a "server."

Overview of the Sockets Interface



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 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.

Socket Programming Cliches

Network Byte Ordering

- Network is big-endian, host may be big- or little-endian
- Functions work on 16-bit (short) and 32-bit (long) values
- htons() / htonl() : convert host byte order to network byte order
- ntohs() / ntohl(): convert network byte order to host byte order
- Use these to convert network addresses, ports, …

Structure Casts

- You will see a lot of ‘structure casts’

```
struct sockaddr_in serveraddr;
/* fill in serveraddr with an address */
…
/* Connect takes (struct sockaddr *) as its second argument */
connect(clientfd, (struct sockaddr *) &serveraddr,
     sizeof(serveraddr));
…
```

Socket Programming Help

man is your friend (aka RTFM)

- man accept
- man select
- Etc.

The manual page will tell you:

- What #include<> directives you need at the top of your source code
- The type of each argument
- The possible return values
- The possible errors (in errno)

Socket Address Structures

Generic socket address:

- For address arguments to `connect`, `bind`, and `accept`.

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

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) */
};
```

Reliable I/O (RIO) Summary

I/O Package Developed by David O'Hallaron

- http://csapp.cs.cmu.edu/public/code.html (csapp.{h,c})
- Allows mix of buffered and unbuffered I/O

Important Functions

`rio_writen(int fd, void *buf, size_t n)`

- Writes `n` bytes from buffer `buf` to file `fd`.

`rio_readlineb(rio_t *rp, void *buf, size_t maxn)`

- Read complete text line from file `rp` into buffer `buf`.
  - » Line must be terminated by newline (`\n`) character
- Up to maximum of `maxn` bytes

Used Here For Illustrative Purposes Only

- You may want to use read()/write() for your projects instead
- You will need to check error returns
- Reading a whole line won't always make sense (more later)
- NOTE: *RIO functions capitalize first letter!! You must fix this!*
  - Accept() .vs. accept()

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);

    while (Fgets(buf, MAXLINE, stdin) != NULL) {
        Rio_writen(clientfd, buf, strlen(buf));
        Rio_readlineb(&rio, buf, MAXLINE);
        Fputs(buf, stdout);
    }
    Close(clientfd);
    exit(0);
}
```

Send line to server

Receive line from server

Client-side Programming

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;
  serveraddr.sin_port = htons(port);
  bcopy((char *)hp->h_addr,
        (char *)&serveraddr.sin_addr.s_addr, hp->h_length);

  /* Establish a connection with the server */
  if (connect(clientfd, (struct sockaddr *) &serveraddr,
       sizeof(serveraddr)) < 0)
    return -1;
  return clientfd;
}
```

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

Echo Client: `open_clientfd` (`socket`)

`socket` creates a socket descriptor on the client.

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

```
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;
bcopy((char *)hp->h_addr,
      (char *)&serveraddr.sin_addr.s_addr, hp->h_length);
serveraddr.sin_port = htons(port);
```

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 `sockfd`.

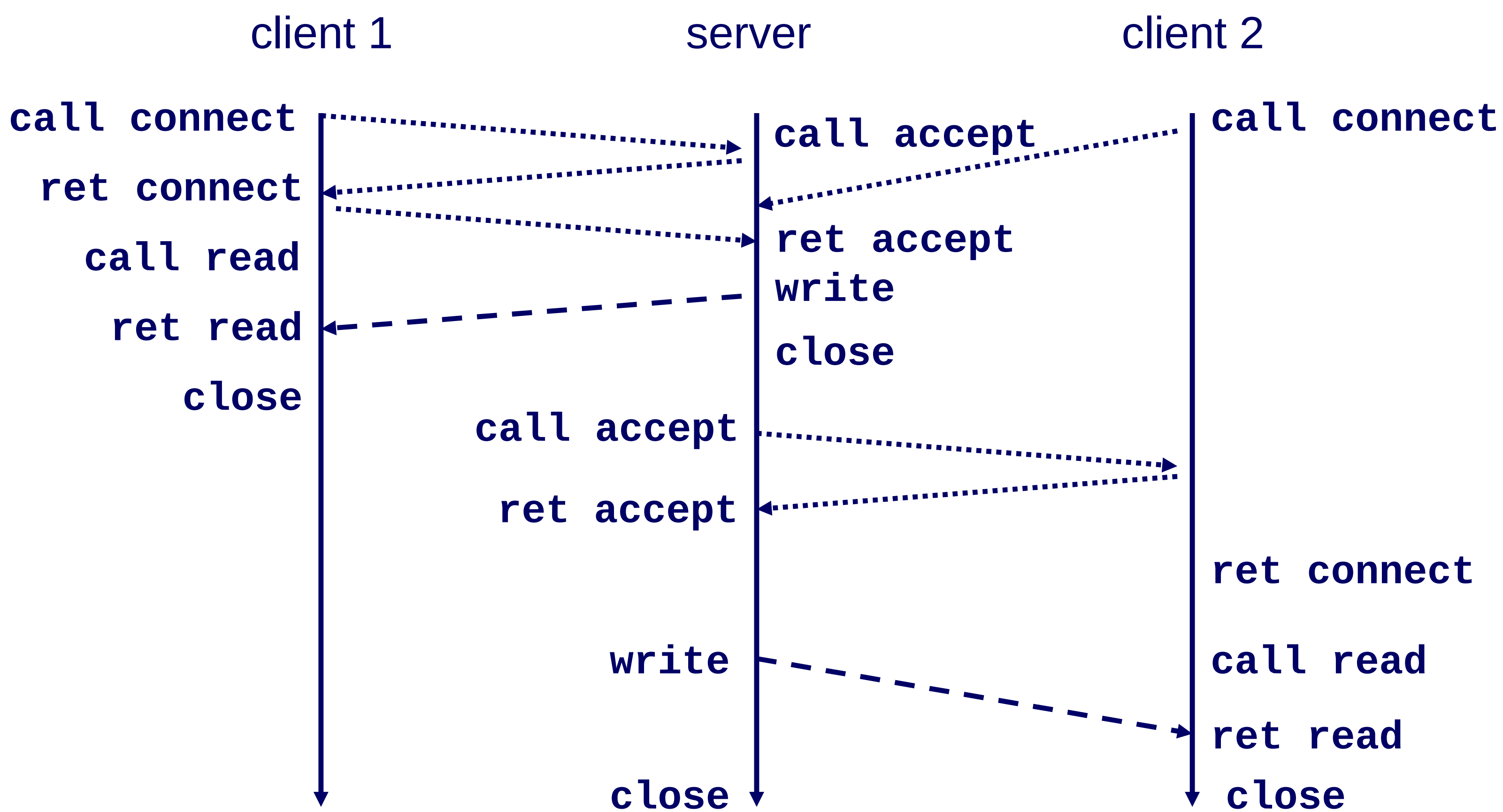
```
  int clientfd;                      /* socket descriptor */
  struct sockaddr_in serveraddr;     /* server address */
  typedef struct sockaddr SA;        /* generic sockaddr */
...
  /* Establish a connection with the server */
  if (connect(clientfd, (SA *)&serveraddr, sizeof(serveraddr)) < 0)
    return -1;
  return clientfd;
}
```

Server-side Programming

Servers and sockets – 1 isn't enough

Server must be able to handle multiple requests

Where should pending connections be queued up?



Connected vs. Listening Descriptors

Listening descriptor

- End point for client connection requests.
- Created once and exists for lifetime of the server.

Connected descriptor

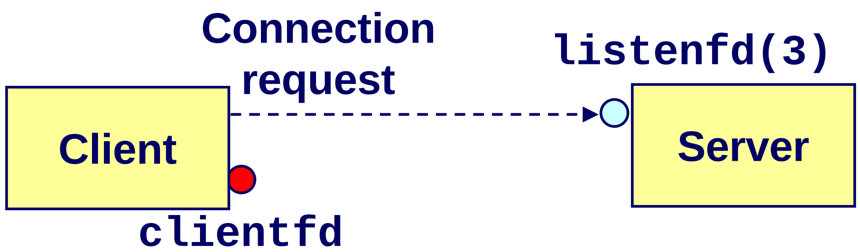
- End point of the connection between client and server.
- A new descriptor is created each time the server accepts a connection request from a client.
- Exists only as long as it takes to service client.

Why the distinction?

- Allows for concurrent servers that can communicate over many client connections simultaneously.

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`.

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 */
   }
}
```

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 (TCP) byte stream connection.**

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

/* Create a socket descriptor */
if ((listenfd = socket(AF_INET, SOCK_STREAM, 0)) < 0)
    return -1;
```

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()` converts 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 */
  if (bind(listenfd, (struct sockaddr *)&serveraddr,
           sizeof(serveraddr)) < 0)
      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, 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: `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: Main Routine

```
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("Fd %d connected to %s (%s:%s)\n",
               connfd, hp->h_name, haddrp, ntohs(clientaddr.sin_port));
        echo(connfd);
        Close(connfd);
    }
}
```

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 */

hp = Gethostbyaddr((const char *)&clientaddr.sin_addr.s_addr,
                   sizeof(clientaddr.sin_addr.s_addr), AF_INET);
haddrp = inet_ntoa(clientaddr.sin_addr);
printf("Fd %d connected to %s (%s:%s)\n",
       connfd, hp->h_name, haddrp, ntohs(clientaddr.sin_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)`.
- IMPORTANT: EOF is a condition, not a particular data byte.

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

Receive line from client

Send line to client

Running Echo Client/Server

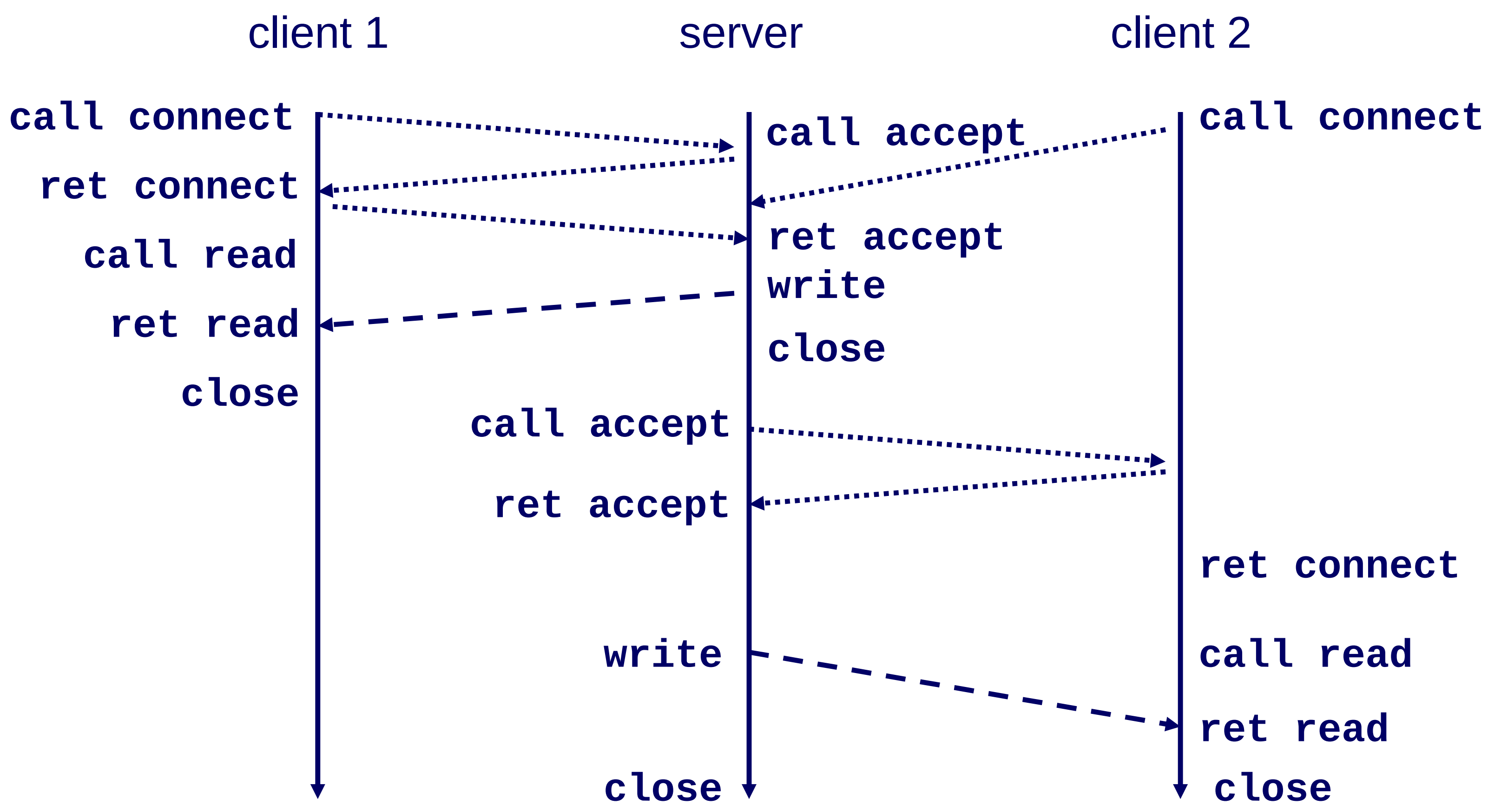
```
[bryant@bryant echo]$ ./echoservers 15441
fd 4 connected to BRYANT-TP2.VLSI.CS.CMU.EDU (128.2.222.198:3507)
Server received 12 (12 total) bytes on fd 4
```

```
[bryant@bryant-tp2 echo]$ ./echoclient bryant.vlsi.cs.cmu.edu 15441
hello world
hello world
```

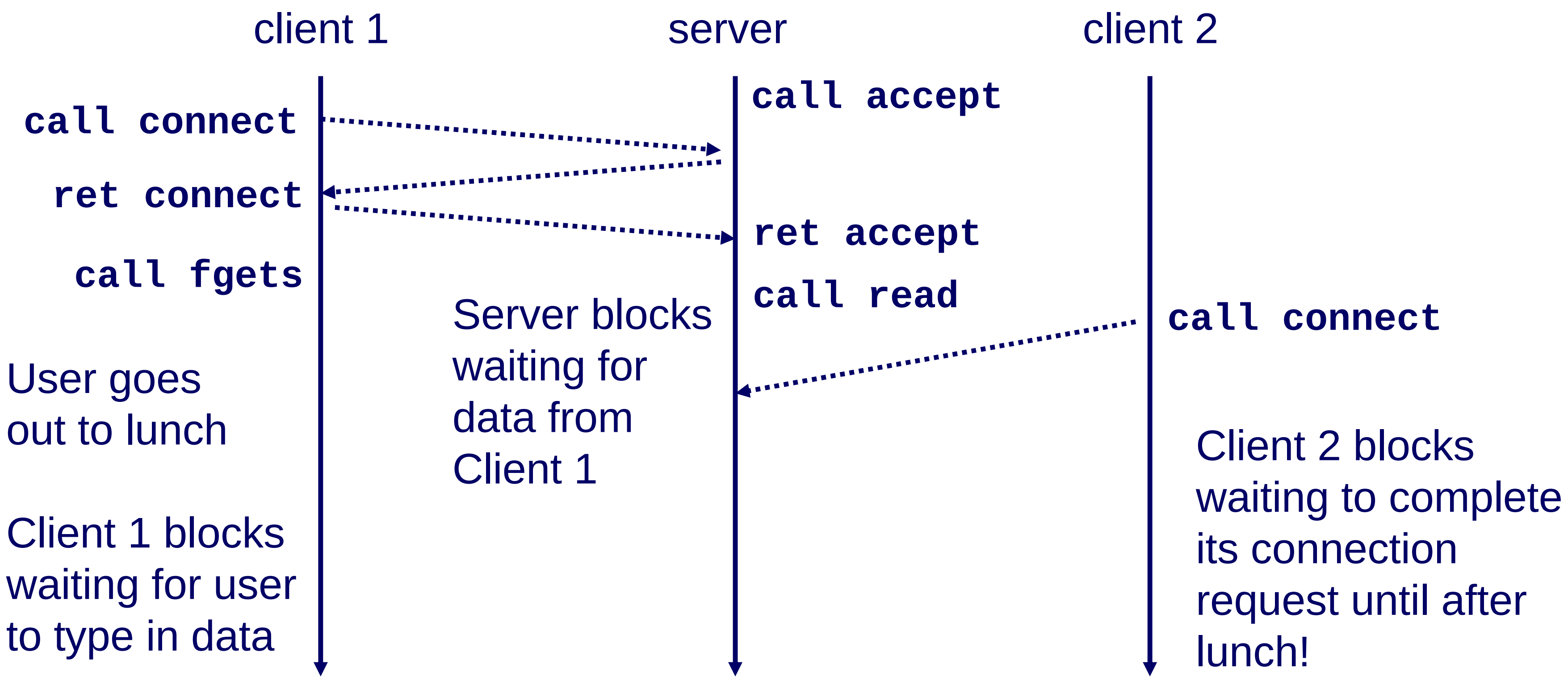
Types of Server Implementations

Iterative Servers

Iterative servers process one request at a time.



Fundamental Flaw of Iterative Servers

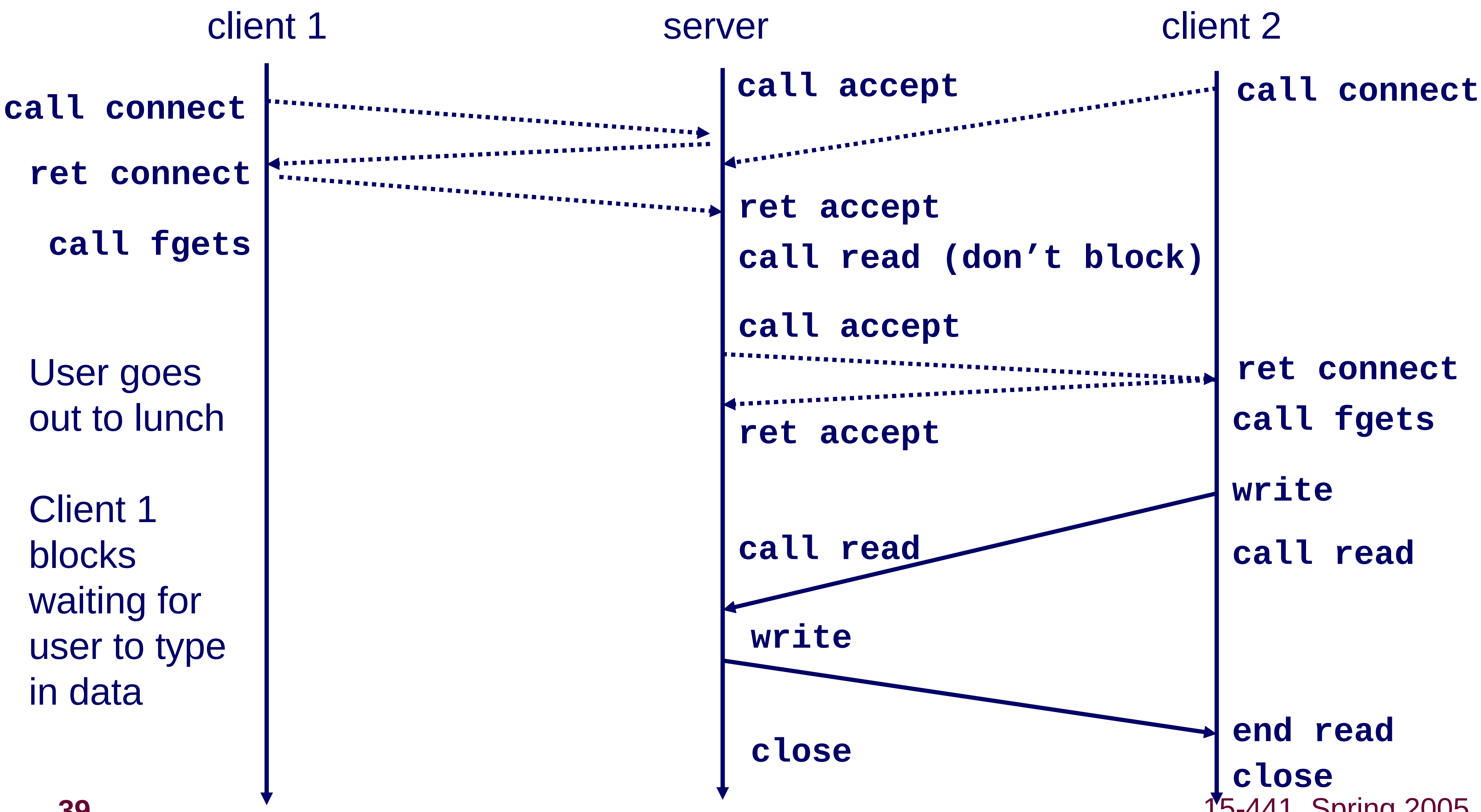


Solution: use *concurrent servers* instead.

- **Concurrent servers use multiple concurrent flows to serve multiple clients at the same time.**

Concurrent Servers

Concurrent servers handle multiple requests concurrently.



Possible Mechanisms for Creating Concurrent Flows

1. Processes

- Kernel automatically interleaves multiple logical flows.
- Each flow has its own private address space.

2. I/O multiplexing with `select()`

Our Focus

- User manually interleaves multiple logical flows.
- Each flow shares the same address space.
- Popular for high-performance server designs.

3. Threads

- Kernel automatically interleaves multiple logical flows.
- Each flow shares the same address space.

Event-Based Concurrent Servers Using I/O Multiplexing

Maintain a pool of connected descriptors.

Repeat the following forever:

- Use the Unix `select` function to block until:
  - (a) New connection request arrives on the listening descriptor.
  - (b) New data arrives on an existing connected descriptor.
- If (a), add the new connection to the pool of connections.
- If (b), read any available data from the connection
  - Close connection on EOF and remove it from the pool.

The `select` Function

`select()` sleeps until one or more file descriptors in the set `readset` ready for reading or one or more descriptors in `writeset` ready for writing

```
#include <sys/select.h>

int select(int maxfdp1, fd_set *readset, fd_set *writeset,
NULL, NULL);
```

`readset`

- Opaque bit vector (max FD_SETSIZE bits) that indicates membership in a *descriptor set.*
  - On Linux machines, FD_SETSIZE = 1024
- If bit k is 1, then descriptor k is a member of the descriptor set.
- When call **`select`**, should have readset indicate which descriptors to test

`writeset`

- **`writeset`** is similar but refers to descriptors ready for writing

`maxfdp1`

- Maximum descriptor in descriptor set plus 1.
- Tests descriptors 0, 1, 2, ..., maxfdp1 - 1 for set membership.

`select()` returns the number of ready descriptors and keeps on each bit of `readset` for which corresponding descriptor is ready

Macros for Manipulating Set Descriptors

```
void FD_ZERO(fd_set *fdset);
```

- Turn off all bits in `fdset`.

```
void FD_SET(int fd, fd_set *fdset);
```

- Turn on bit `fd` in `fdset`.

```
void FD_CLR(int fd, fd_set *fdset);
```

- Turn off bit `fd` in `fdset`.

```
int FD_ISSET(int fd, *fdset);
```

- Is bit `fd` in `fdset` turned on?

Event-based Concurrent Echo Server

```
/*
 * echoservers.c - A concurrent echo server based on select
 */
#include "csapp.h"

typedef struct { /* represents a pool of connected descriptors */
    int maxfd;        /* largest descriptor in read_set */
    fd_set read_set;  /* set of all active descriptors */
    fd_set ready_set; /* subset of descriptors ready for reading  */
    int nready;       /* number of ready descriptors from select */
    int maxi;         /* highwater index into client array */
    int clientfd[FD_SETSIZE];    /* set of active descriptors */
    rio_t clientrio[FD_SETSIZE]; /* set of active read buffers */
} pool;

int byte_cnt = 0; /* counts total bytes received by server */
```

Event-based Concurrent Server (cont)

```
int main(int argc, char **argv)
{
    int listenfd, connfd, clientlen = sizeof(struct sockaddr_in);
    struct sockaddr_in clientaddr;
    static pool pool;

    listenfd = Open_listenfd(argv[1]);
    init_pool(listenfd, &pool);

    while (1) {
        pool.ready_set = pool.read_set;
        pool.nready = Select(pool.maxfd+1, &pool.ready_set,
                             NULL, NULL, NULL);

        if (FD_ISSET(listenfd, &pool.ready_set)) {
            connfd = Accept(listenfd, (SA *)&clientaddr,&clientlen);
            add_client(connfd, &pool);
        }
        check_clients(&pool);
    }
}
```

Event-based Concurrent Server (cont)

```
/* initialize the descriptor pool */
void init_pool(int listenfd, pool *p)
{
    /* Initially, there are no connected descriptors */
    int i;
    p->maxi = -1;
    for (i=0; i< FD_SETSIZE; i++)
        p->clientfd[i] = -1;

    /* Initially, listenfd is only member of select read set */
    p->maxfd = listenfd;
    FD_ZERO(&p->read_set);
    FD_SET(listenfd, &p->read_set);
}
```

Event-based Concurrent Server (cont)

```
void add_client(int connfd, pool *p)  /* add connfd to pool p */
{
    int i;
    p->nready--;

   for (i = 0; i < FD_SETSIZE; i++)  /* Find available slot */
        if (p->clientfd[i] < 0) {
            p->clientfd[i] = connfd;
            Rio_readinitb(&p->clientrio[i], connfd);

            FD_SET(connfd, &p->read_set); /* Add desc to read set */

            if (connfd > p->maxfd) /* Update max descriptor num */
                p->maxfd = connfd;
            if (i > p->maxi) /* Update pool high water mark */
                p->maxi = i;
            break;
        }
    if (i == FD_SETSIZE) /* Couldn't find an empty slot */
        app_error("add_client error: Too many clients");
}
```

Event-based Concurrent Server (cont)

```
void check_clients(pool *p) { /* echo line from ready descs in pool p */
    int i, connfd, n;
    char buf[MAXLINE];
    rio_t rio;

    for (i = 0; (i <= p->maxi) && (p->nready > 0); i++) {
        connfd = p->clientfd[i];
        rio = p->clientrio[i];

        /* If the descriptor is ready, echo a text line from it */
        if ((connfd > 0) && (FD_ISSET(connfd, &p->ready_set))) {
            p->nready--;
            if ((n = Rio_readlineb(&rio, buf, MAXLINE)) != 0) {
                byte_cnt += n;
                Rio_writen(connfd, buf, n);
            }
            else {/* EOF detected, remove descriptor from pool */
                Close(connfd);
                FD_CLR(connfd, &p->read_set);
                p->clientfd[i] = -1;
            }
        }
    }
}
```

Pro and Cons of Event-Based Designs

+ One logical control flow.

+ Can single-step with a debugger.

+ No process or thread control overhead.
  - Design of choice for high-performance Web servers and search engines.

- Significantly more complex to code than process- or thread-based designs.

- Can be vulnerable to denial of service attacks
  - How?

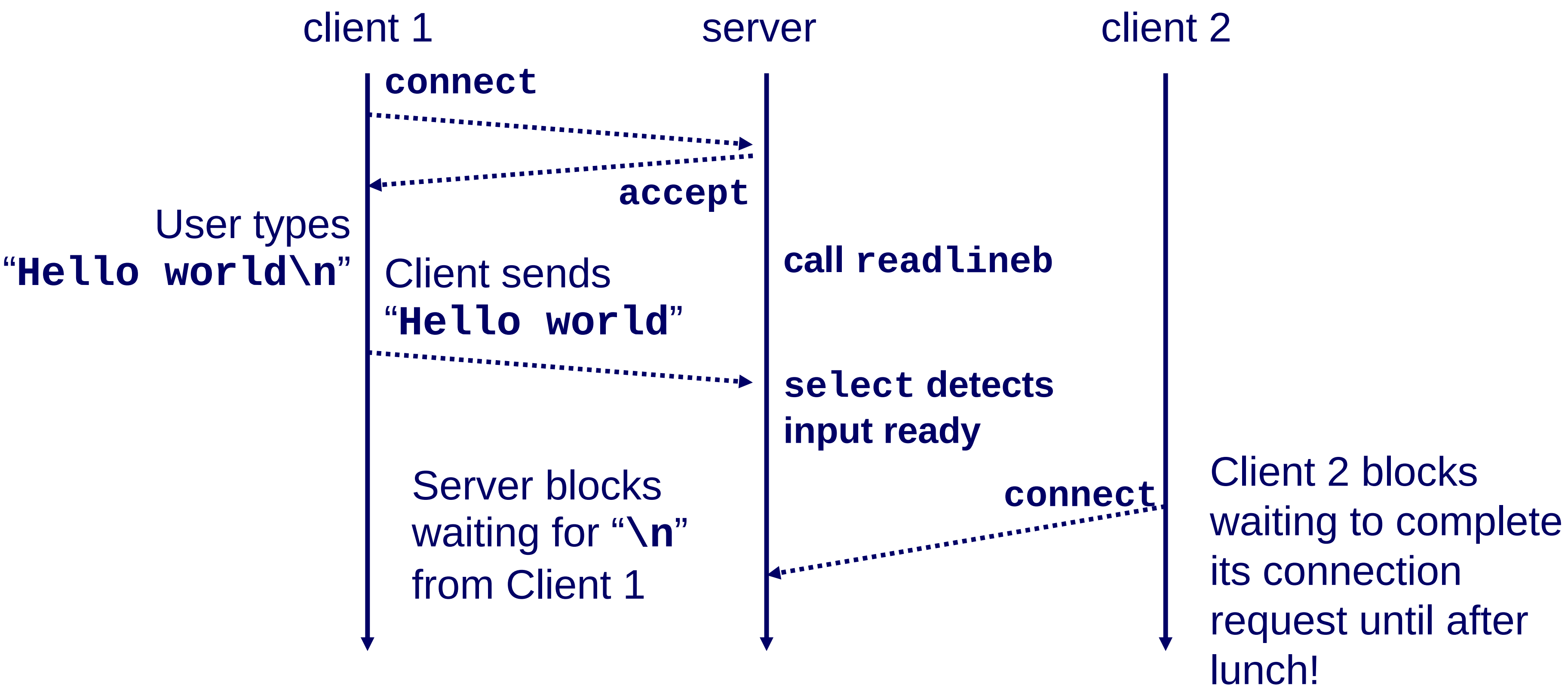
Attack #1

Overwhelm Server with Connections

- Limited to FD_SETSIZE – 4 (typically 1020) connections

Defenses?

Attack #2: Partial Lines



- **Client gets attention of server by sending partial line**
- **Server blocks until line completed**

Flaky Client

```
while (Fgets(buf, MAXLINE, stdin) != NULL) {
    Rio_writen(clientfd, buf, strlen(buf)-1);
    Fgets(buf, MAXLINE, stdin);  /* Read & ignore line */
    Rio_writen(clientfd, "\n", 1);
    Rio_readlineb(&rio, buf, MAXLINE);
    Fputs(buf, stdout);
}
```

- **Sends everything up to newline**
- **Doesn’t send newline until user types another line**
- **Meanwhile, server will block**

Implementing a Robust Server

Break Up Reading Line into Multiple Partial Reads

- Every time connection selected, read as much as is available
- Construct line in separate buffer for each connection

Must Use Unix Read

```
read(int fd, void *buf, size_t maxn)
```

- Read as many bytes as are available from file `fd` into buffer `buf`.
- Up to maximum of `maxn` bytes

Cannot Use RIO Version

```
rio_readn(int fd, void *buf, size_t n)
```

- Read n bytes into buffer `buf`.
- Blocks until all n read or EOF

Robust Server

```
/*
 * echoserverub.c - A robust, concurrent echo server based on select
 */
#include "csapp.h"

typedef struct { /* represents a pool of connected descriptors */
    int maxfd;        /* largest descriptor in read_set */
    fd_set read_set;  /* set of all active descriptors */
    fd_set ready_set; /* subset of descriptors ready for reading  */
    int nready;       /* number of ready descriptors from select */
    int maxi;         /* highwater index into client array */
    int clientfd[FD_SETSIZE];    /* set of active descriptors */
    char clientbuf[FD_SETSIZE][MAXBUF]; /* set of read buffers */
    int clientcnt[FD_SETSIZE]; /* Count of characters in buffers */
} pool;

int byte_cnt = 0; /* counts total bytes received by server */
```

Robust Server Loop

```
void check_clients(pool *p)
{
    int i, connfd, n;
    for (i = 0; (i <= p->maxi) && (p->nready > 0); i++) {
        connfd = p->clientfd[i];
        char *buf = p->clientbuf[i]; /* Private buffer */
        int cnt =   p->clientcnt[i]; /* Number of chars read so far */
        if ((connfd > 0) && (FD_ISSET(connfd, &p->ready_set))) {
            p->nready--;
            if ((n = Read(connfd, buf+cnt, MAXBUF-cnt)) != 0) {
                byte_cnt += n; cnt += n;
                if (buf[cnt-1] == '\n') {
                  Write(connfd, buf, cnt); /* End of line */
                  p->clientcnt[i] = 0;
                } else
                  p->clientcnt[i] = cnt;
            }
        }
    }
}
```

NOTE (Just to complicate things…)

If a client sends x bytes of data in one write() call, it is NOT guaranteed that all x bytes will be received in a single read() call by the server.

i.e., the following scenario is possible:

- Client writes "Hello world\n" to server
- Server's select() notices & unblocks, server then calls read()
- read() returns "Hell"
- A subsequent call to read() returns "o w"
- A subsequent call to read() returns "orld\n"

Server's solution: maintain a buffer for each of your clients, and only process the buffer's contents when a message has been received in full (note: the type of application determines what a 'message' is, and what indicates it has been fully received)

Conceptual Model

Maintain State Machine for Each Connection

- **First Version: State is just identity of connfd**
- **Second Version: State includes partial line + count of characters**

`select` Determines Which State Machine to Update

- **First Version: Process entire line**
- **Second Version: Process as much of line as is available**

Design Issue

- **Must set granularity of state machine to avoid server blocking**

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 original echo client and server are developed in *Computer Systems*: *A Programmer's Perspective*.

- Available from `csapp.cs.cmu.edu`
- Compile and run them for yourselves to see how they work.
- Feel free to borrow any of this code.
- But be careful---it isn't sufficiently robust for our programming assignments
  - » Most routines exit when any kind of error encountered

For More Information

What's inside the RIO wrappers

```
int Select(int  n, fd_set *readfds, fd_set *writefds,
           fd_set *exceptfds, struct timeval *timeout) {
    int rc;
    if ((rc = select(n, readfds, writefds, exceptfds, timeout)) < 0)
        unix_error("Select error");
    return rc;
}
```

GDB and Version Control (RCS/CVS)

Tools to help make programming task simpler

- GDB helps the debugging task
- RCS or CVS help with the task of maintaining your code across multiple revisions

Neither system is magic

- Debugging
  - Program defensively – check error returns, buffer sizes
  - Build program in a modular fashion
  - Print sensible error messages
    - » May want to do better than the built-in wrapper functions
- Version control
  - Keep a clear idea of who is doing what
  - Build program in a modular fashion
    - » Define interfaces between modules early and try not to change them too much

Debugging with GDB

Prepare program for debugging

- Compile with "`-g`" (keep full symbol table)
- Don't use compiler optimization ("`-O`", "`–O2`", …)

Two main ways to run gdb

- On program directly
  - `gdb progname`
  - Once gdb is executing we can execute the program with:
    - » `run args`
    - » Can use shell-style redirection e.g. `run < infile > /dev/null`
- On a core (post-mortem)
  - `gdb progname core`
  - Useful for examining program state at the point of crash

Extensive in-program documentation exists

- `help` (or `help <topic>` or `help <command>`)

Controlling Your Program With GDB

Stopping your program with breakpoints

- **Program will run until it encounters a breakpoint**
  - To start running again: `cont`
- **Break command format**
  - `break foo.c:4` stops at the 4th source line of `foo.c`
  - `break 16` stops at the 16th source line of the current source file
  - `break main` stops upon entry to the `main()` function

Stop your program with SIGINT (CTRL-C)

- **Useful if program hangs (sometimes)**

Stepping through your program

- **`step N` command: steps through N source lines (default 1)**
- **`next` is like `step` but it treats function calls as a single line**

Hint: avoid writing mega-expressions

- **Hard to step through `foo(bar(tmp = baz(), tmp2 = baz2()))`**

Examining the State of Your Program

`backtrace` (`bt` for short)

- Shows stack trace (navigate procedures using up and down)
- `bt full` prints out all available local variables as well

`print EXP`

- Print the value of expression
- Can print out values in variables

`x/<count><format><size> ADDR`

- Examine a memory region at ADDR
- Count is the number of items to display (default: 1)
- Format is a single letter code
  - o(octal), x(hex), d(decimal), u(unsigned decimal), t(binary), f(float), a(address), i(instruction), c(char) and s(string)
- Size is the size of the items (single letter code)
  - b(byte), h(halfword), w(word), g(giant, 8 bytes)

Version Control with RCS

Version control systems:

- Maintain multiple versions of a file
  - Allow rollback to old versions
  - Enforce documentation of changes
- Allows multiple programmers to work on a project without accidentally editing the same file
  - Files must be ‘checked out’ for reading or writing

RCS maintains a database of all revisions

- Make a subdirectory called ‘RCS’ in each working directory
  - Otherwise RCS will do its business in your directory – ugly!
- If your file is called ‘assignment1/foo.c’, RCS keeps update history in ‘assignment1/RCS/foo.c,v’
- Current version of ‘foo.c’ is maintained in ‘foo.c,v’
  - ‘deltas’ allow retrieval of older versions

Creating RCS Files

After making 'RCS' subdirectory…

Initialize RCS for your file `mysource.c` (assume you have already created it) by checking it in (`ci`)

```
[geoffl@ux3 ~/tmp]$ ci mysource.c
RCS/mysource.c,v  <--  mysource.c
enter description, terminated with single '.' or end of file:
NOTE: This is NOT the log message!
>> This source file contains a simple algorithm to solve the Halting
Problem.
>> .
initial revision: 1.1
done
```

Can also create a blank file with `rcs –i mysource.c`

Either way, this produces version 1.1

Checking out files

In previous example, after `ci`, `mysource.c` is gone!

To retrieve `mysource.c`, use co command ('check out')

```
[geoffl@ux3 ~/tmp]$ ls -l
total 2
drwxr-xr-x    2 geoffl   users        2048 Jan 19 15:39 RCS
[geoffl@ux3 ~/tmp]$ co mysource.c
RCS/mysource.c,v  -->  mysource.c
revision 1.1
done
[geoffl@ux3 ~/tmp]$ ls -l
total 3
-r--r--r--    1 geoffl   users         137 Jan 19 15:39 mysource.c
drwxr-xr-x    2 geoffl   users        2048 Jan 19 15:39 RCS
```

Note: permissions don't let us change `mysource.c`

To change `mysource.c`, must acquire lock

- `co –l mysource.c` locks mysource.c so no one else can change it
- Use `ci` to check the code back in when done (adding a log message)

Versions

Each version of the file has a version number

- "release.revision" format – e.g. 4.2 is release 4, revision 2
- Doesn't necessarily correspond to anything about real world version numbers

By default, each `ci` of a changed file increments revision number by 1

Can use `-r` flag to specify version numbers

- Use this with co to retrieve old versions
- Use this with `ci` to specify what a new version should be called
  - Note: can't go backwards!
  - `ci –r1.8 mysource.c` will check in `mysource.c` with version number 1.8
  - `ci –r2 mysource.c` will check in `mysource.c` with version 2.1

Version Control with CVS

Similar to RCS, but newer and with more functionality

- Like RCS, Maintains multiple versions of a file
  - Allow rollback to old versions
  - Enforce documentation of changes
- Allows multiple programmers to work on the same file at the same time
  - Upon checkin, if conflicts exist, the user is notified and can resolve them manually using a diff program (i.e. diff on UNIX, ExamDiff on Windows)
- Easy to use on the UNIX command line
- Has a very, very friendly client for Windows users that integrates into your folder’s file management system called “TortoiseCVS” http://www.tortoisecvs.org/

Version Control continued

RCS and CVS both maintain a database of all revisions

- Make a subdirectory called ‘RCS’ in each working directory
  - Otherwise RCS will do its business in your directory – ugly!
  - Note: CVS does this for you automatically
- If your file is called ‘assignment1/foo.c’, RCS keeps update history in ‘assignment1/RCS/foo.c,v’, CVS similarly
- Current version of ‘foo.c’ is maintained in ‘foo.c,v’
  - ‘deltas’ allow retrieval of older versions

More information about CVS (my personal choice)

- http://www.nongnu.org/cvs/
- http://www.tortoisecvs.org/ for Windows users

More information…

GDB

- Official GDB homepage: http://www.gnu.org/software/gdb/gdb.html
- GDB primer: http://www.cs.pitt.edu/~mosse/gdb-note.html

RCS

- Look at `man rcs`, `man rcsintro`
- Official RCS homepage:
  - http://www.cs.purdue.edu/homes/trinkle/RCS/
- Other useful features
  - `ci –l`: check-in a version but keep the file and the lock
  - `ci –u`: check-in a version but keep a read-only version of file
  - `rcsdiff`: display differences between versions
  - `rcsmerge`: merge changes in different versions of a file
  - Note: you can break locks if necessary
    - » RCS will send e-mail to owner of broken lock

Tips for the past

Find a partner that doesn't procrastinate.

Schedule a *daily* meeting time. DAILY.

- Do a couple hours of work each day.
- Even meeting 3 days a week for a few hours, my partner and I pulled multiple all-nighters. Avoid this by meeting daily.
- Your implementations for each project can be expected to be 5,000 lines of code, plus or minus a few thousand (ours were between 4,000-6,000 lines). Divide that by days and it's not as daunting.

START THE DAY YOU RECEIVE THE PROJECT.

- My personal impression from last year is that the majority of failed/mostly unsuccessful projects failed due to time-related pressure, not content/understanding material pressure
- If you have time to do it, you can do it well. If not…

More tips for the past

If you want to work directly on windows, you can use MinGW or Cygwin, *BUT TEST ON UNIX*

- http://www.mingw.org/
- http://www.cygwin.com/

Most of the APIs you will use will have many functions that return -1 to indicate error. Unlike previous classes, you must be able to recover when appropriate, and handle these errors on a case-by-case basis.

Make buffers for *each* of your clients; don't process a command until you know you've received the entire thing.

Finally…

These projects are about implementing specifications.

Read the writeup at least twice before starting.

PLAN on paper (even draw) BEFORE coding.

PLAN, PLAN, PLAN.

Then coding and debugging will be much easier, and you won't have to delete hundreds of lines of useless code over and over again.

Good luck!