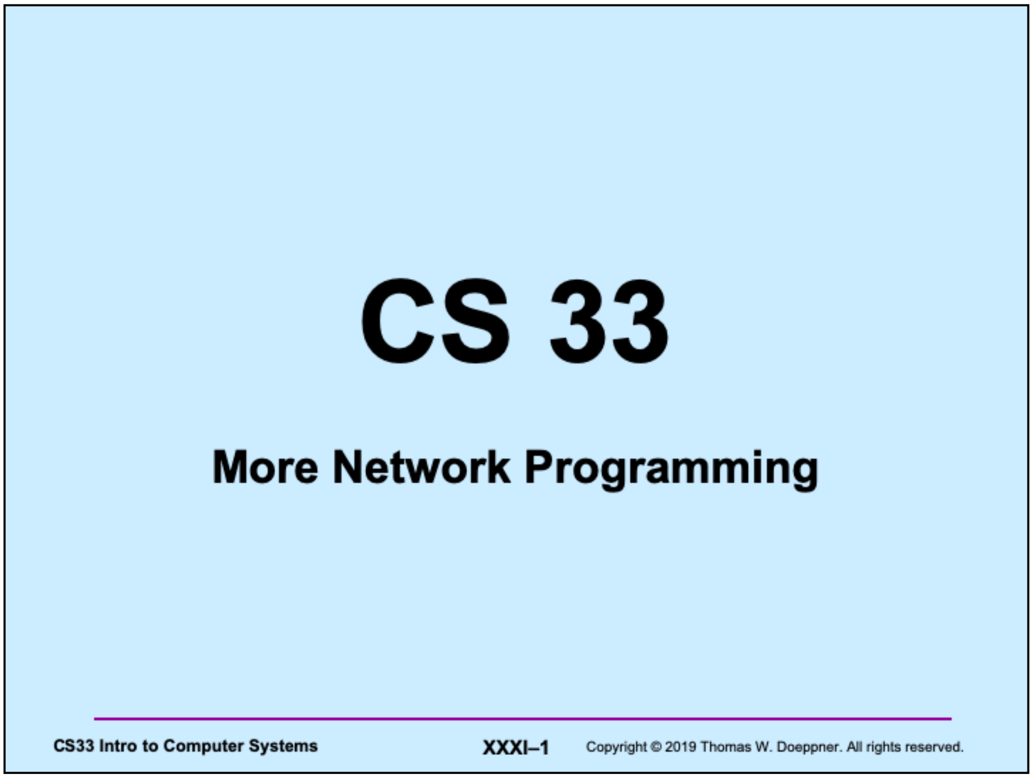
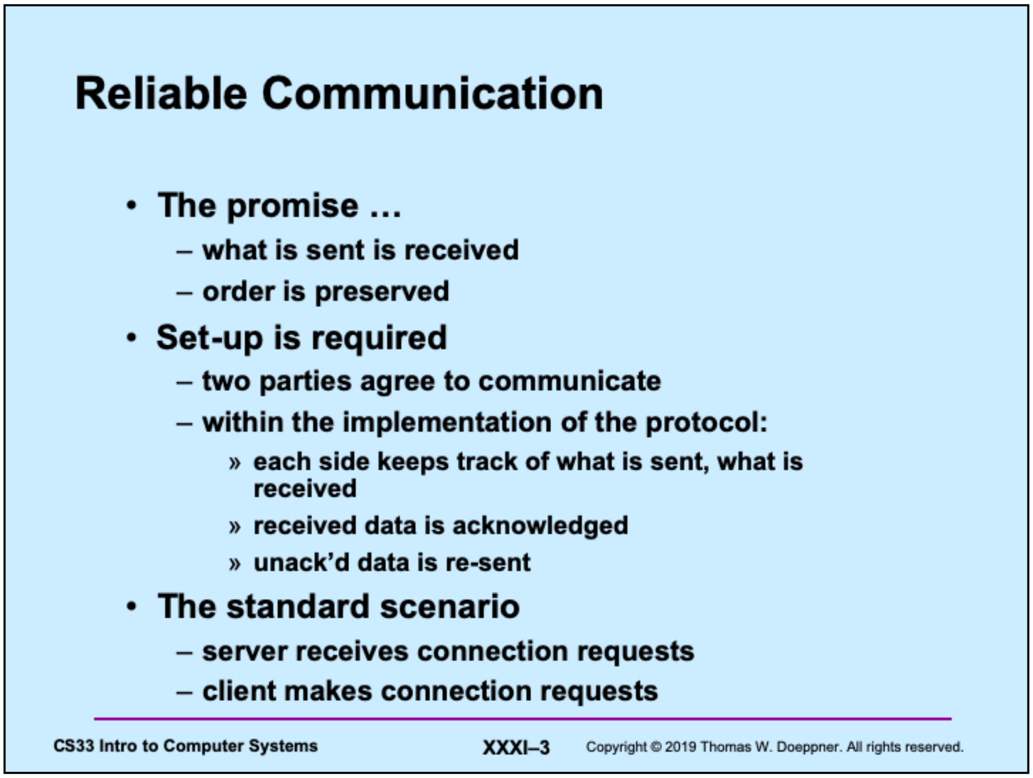


CS 33

More Network Programming

Client-Server Interaction

- Client sends requests to server
- Server responds
- Server may deal with multiple clients at once
- Client may contact multiple servers



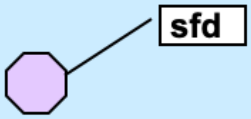
Reliable Communication

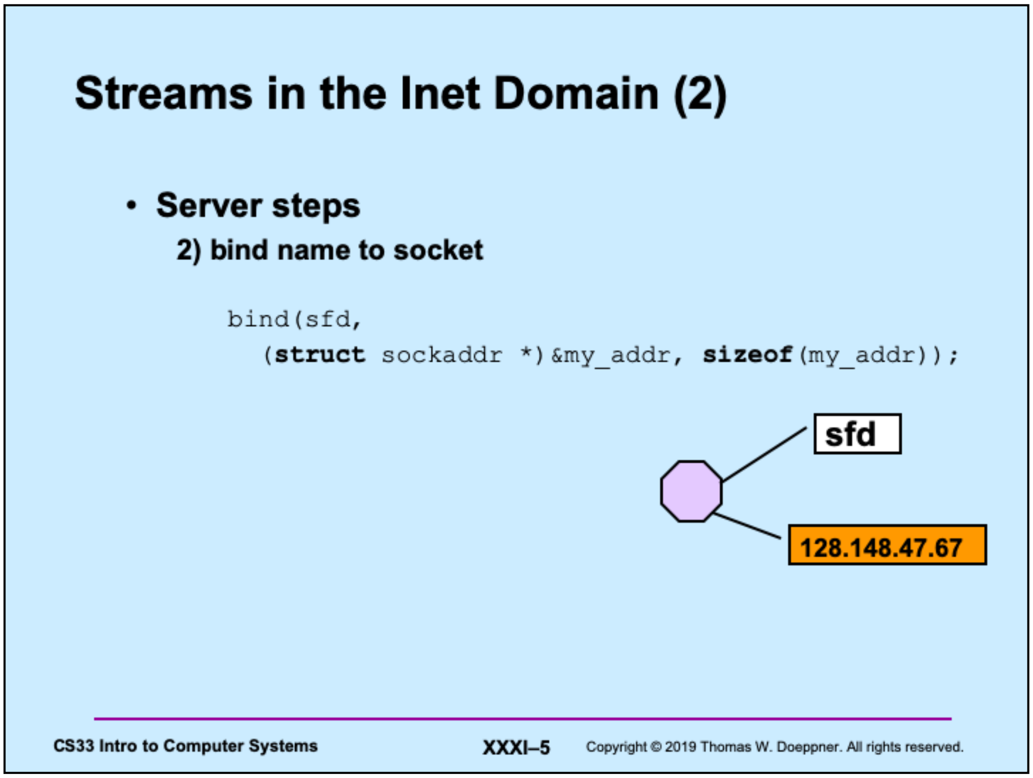
- The promise …
  - – what is sent is received
  - – order is preserved
- Set-up is required
  - – two parties agree to communicate
  - – within the implementation of the protocol:
    - » each side keeps track of what is sent, what is received
    - » received data is acknowledged
    - » unack'd data is re-sent
- The standard scenario
  - – server receives connection requests
  - – client makes connection requests

Streams in the Inet Domain (1)

- **Server steps**
  1) create socket

```
sfd = socket(AF_INET, SOCK_STREAM, 0);
```



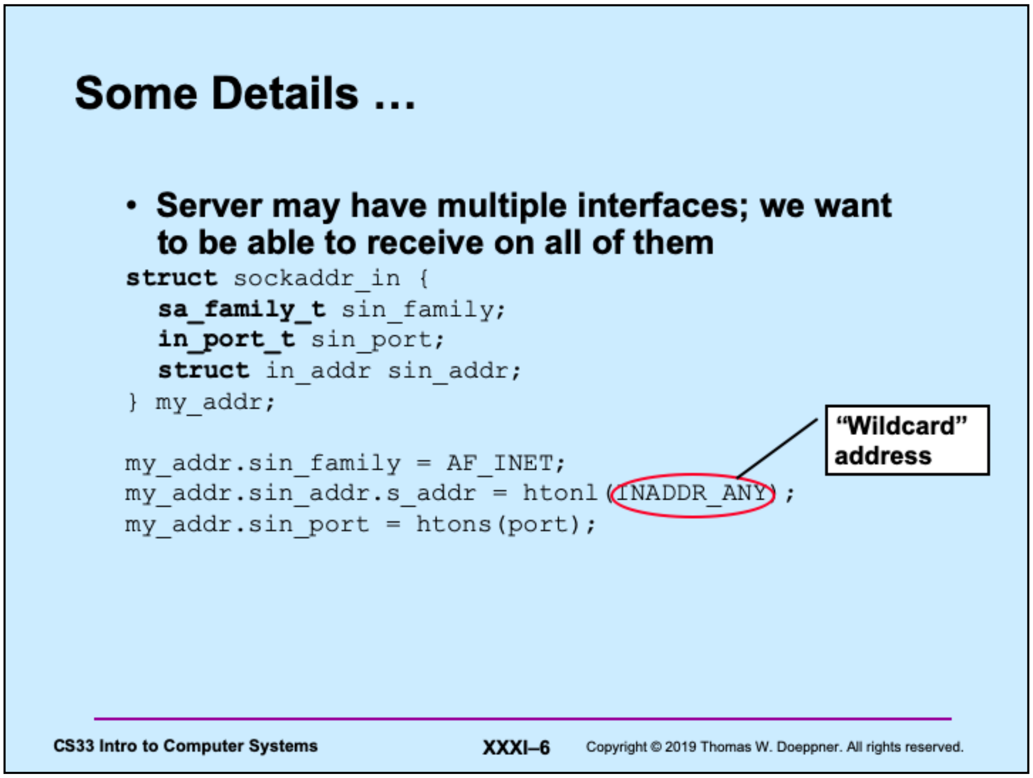


Streams in the Inet Domain (2)

- **Server steps**
  - **2) bind name to socket**

```
bind(sfd,
   (struct sockaddr *)&my_addr, sizeof(my_addr));
```

sfd
128.148.47.67



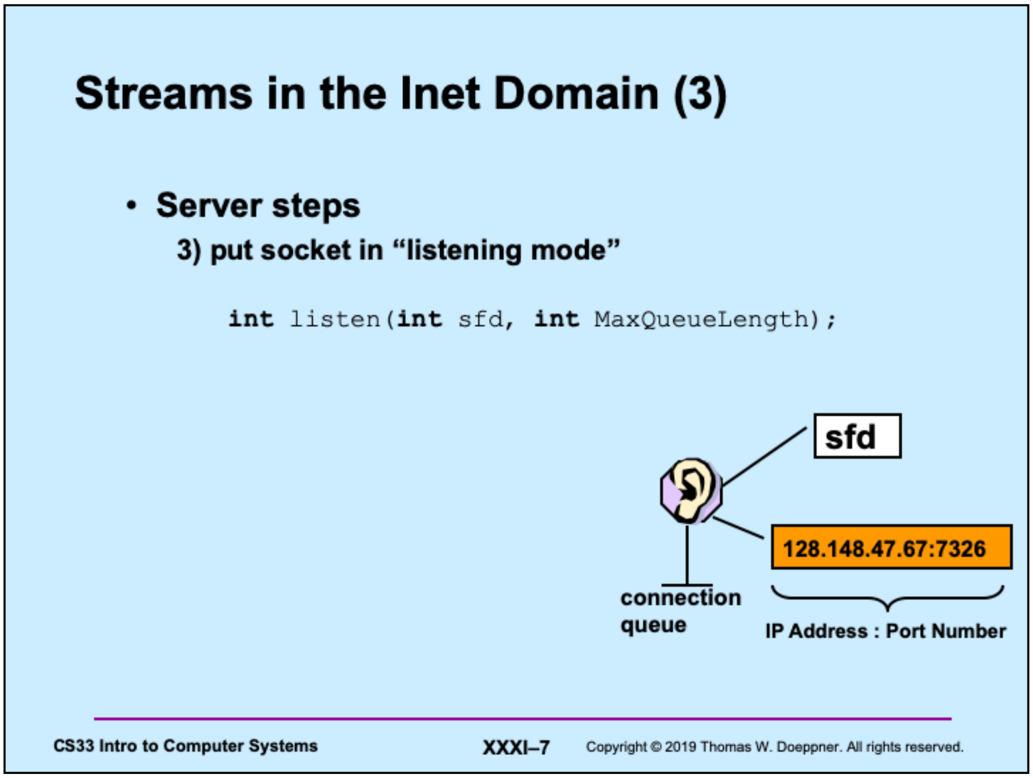
Some Details …

- Server may have multiple interfaces; we want to be able to receive on all of them

```
struct sockaddr_in {
  sa_family_t sin_family;
  in_port_t sin_port;
  struct in_addr sin_addr;
} my_addr;

my_addr.sin_family = AF_INET;
my_addr.sin_addr.s_addr = htonl(INADDR_ANY);
my_addr.sin_port = htons(port);
```

“Wildcard” address

A machine might have multiple addresses — this is often the case for servers. Rather than having to specify all of them, one simply gives the “wildcard” address, meaning all the addresses on the machine. This is useful even on a machine with just one network interface, since the wildcard address in that case refers to just the one interface.



Streams in the Inet Domain (3)

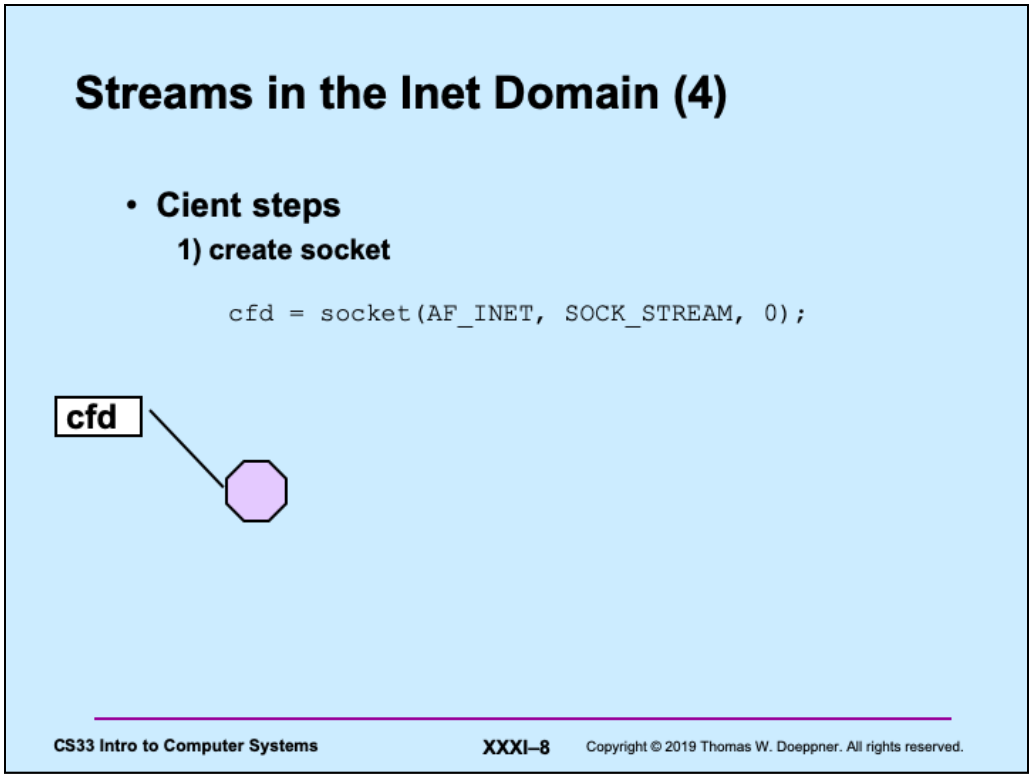
- **Server steps**

  3) put socket in “listening mode”

```
int listen(int sfd, int MaxQueueLength);
```

sfd
128.148.47.67:7326
IP Address : Port Number
connection queue

The *listen* system call tells the OS that the process would like to receive connections from clients via the indicated socket. The MaxQueueLength argument is the maximum number of connections that may be queued up, waiting to be accepted. Its maximum value is in /proc/sys/net/core/somaxconn (and is currently 128).

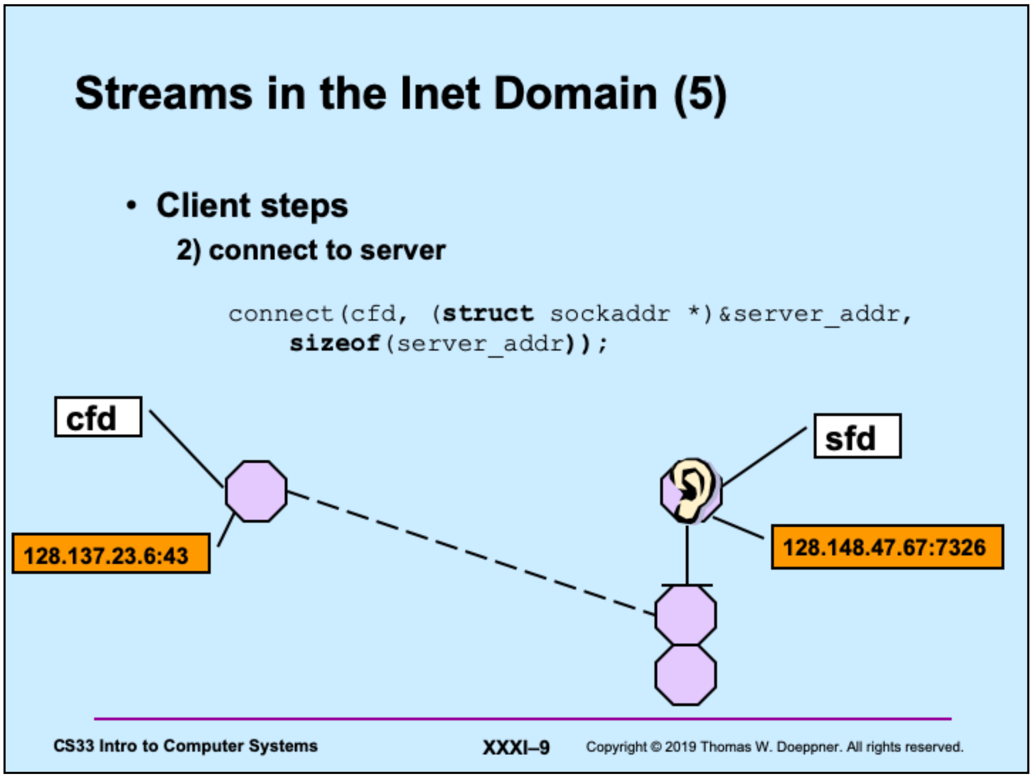


Streams in the Inet Domain (4)

- **Cient steps**

  1) create socket

```
cfd = socket(AF_INET, SOCK_STREAM, 0);
```



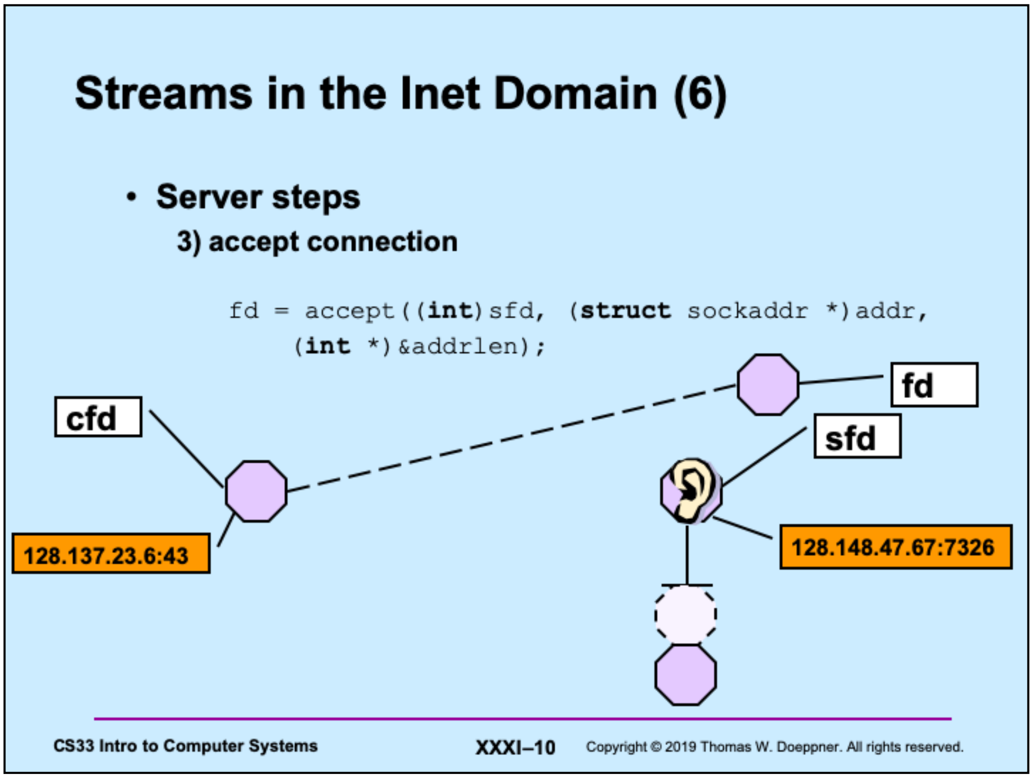
Streams in the Inet Domain (5)

- **Client steps**

  2) connect to server

```
connect(cfd, (struct sockaddr *)&server_addr,
    sizeof(server_addr));
```

The client issues the *connect* system call to initiate a connection with the server. An internet address and port number is automatically assigned to the client's socket, The first argument of connect is a file descriptor referring to the client’s socket. Ultimately this socket will be connected to a socket on the server. Behind the scenes the client OS communicates with the server OS via a protocol-specific exchange of messages. Eventually a connection is established and a new socket is created on the server to represent its end of the connection. This socket is queued on the server’s listening socket, where it stays until the server process accepts the connection (as shown in the next slide).



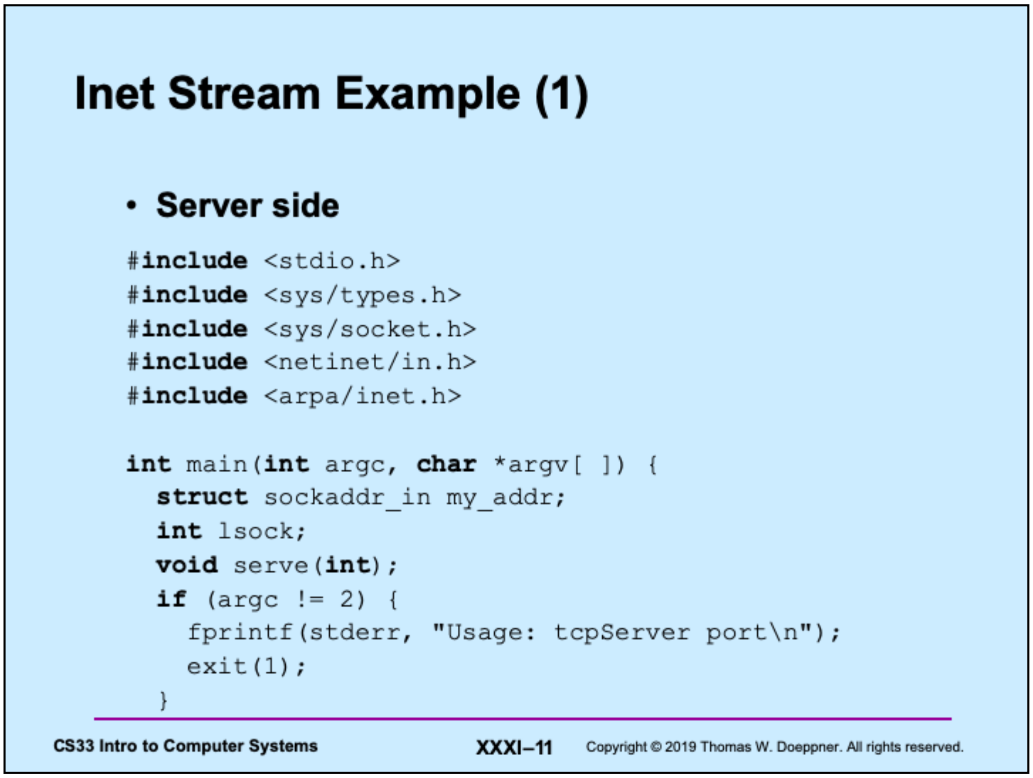
Streams in the Inet Domain (6)

- **Server steps**

  3) accept connection

```
fd = accept((int)sfd, (struct sockaddr *)addr,
    (int *)&addrlen);
```

The server process issues an *accept* system which waits if necessary for a connected socked to appear on the listening socket’s queue, then pulls the first such socket from the queue. This socket is the server end of a connection from a client. A file descriptor is returned that refers to that socket, allowing the process to now communicate with the client.

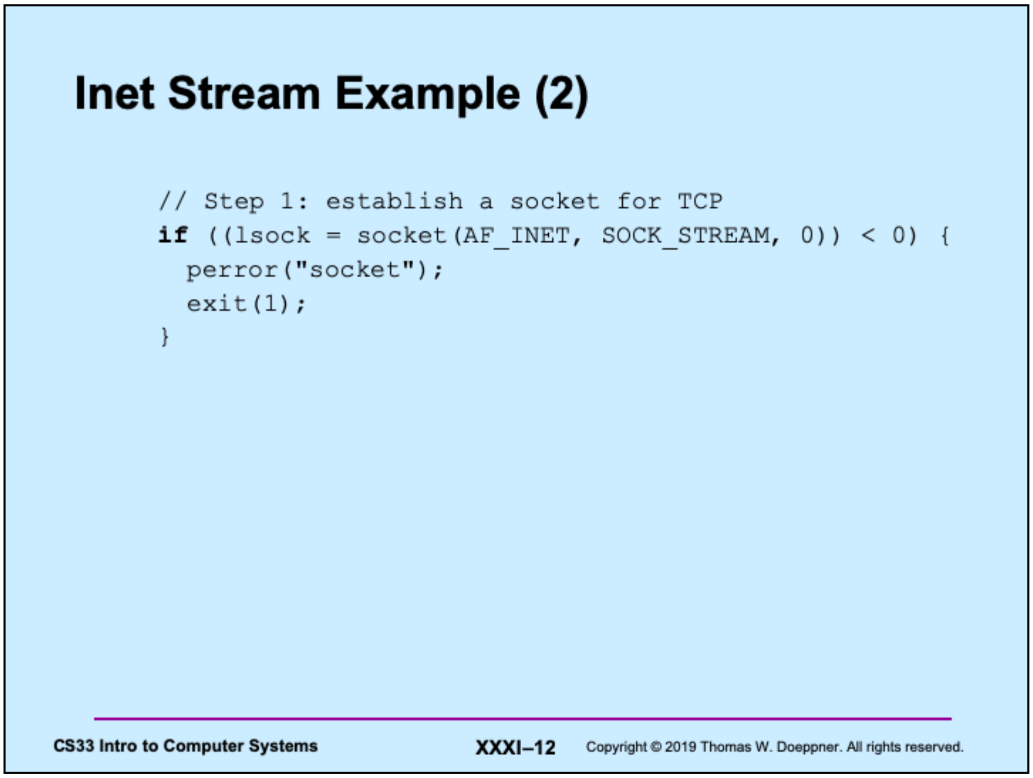


Inet Stream Example (1)

- Server side

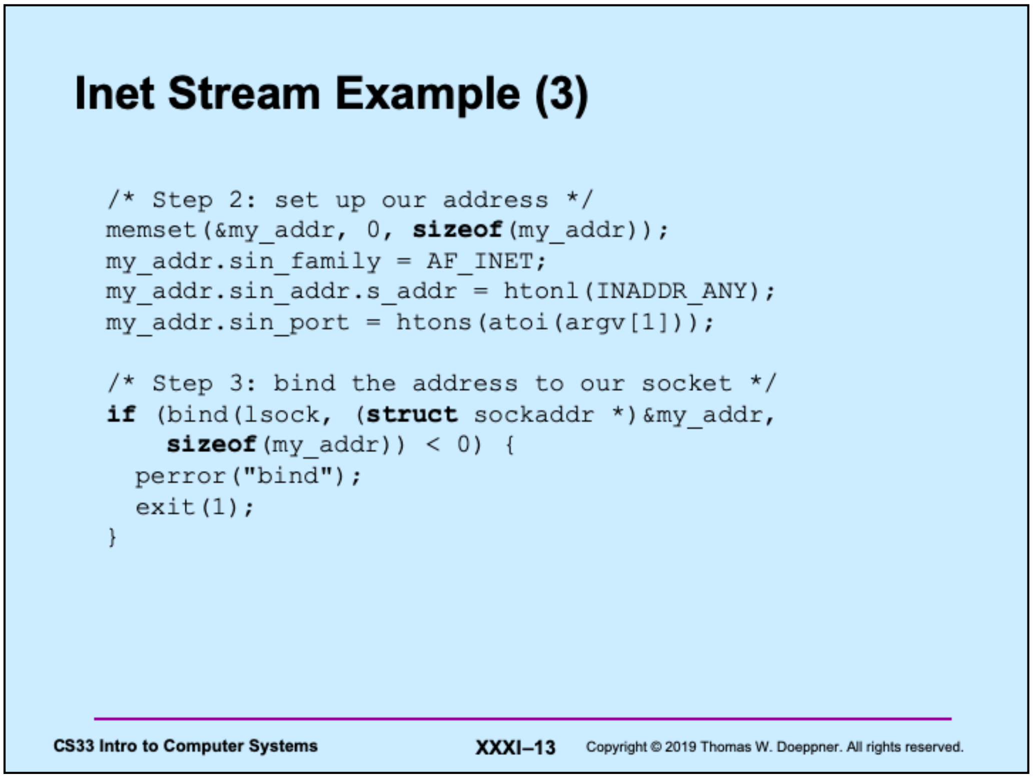
```
#include <stdio.h>
#include <sys/types.h>
#include <sys/socket.h>
#include <netinet/in.h>
#include <arpa/inet.h>

int main(int argc, char *argv[ ]) {
  struct sockaddr_in my_addr;
  int lsock;
  void serve(int);
  if (argc != 2) {
    fprintf(stderr, "Usage: tcpServer port\n");
    exit(1);
  }
```

Here we go through code used for setting up and communicating over a connection using TCP. We start with the server.



Inet Stream Example (2)

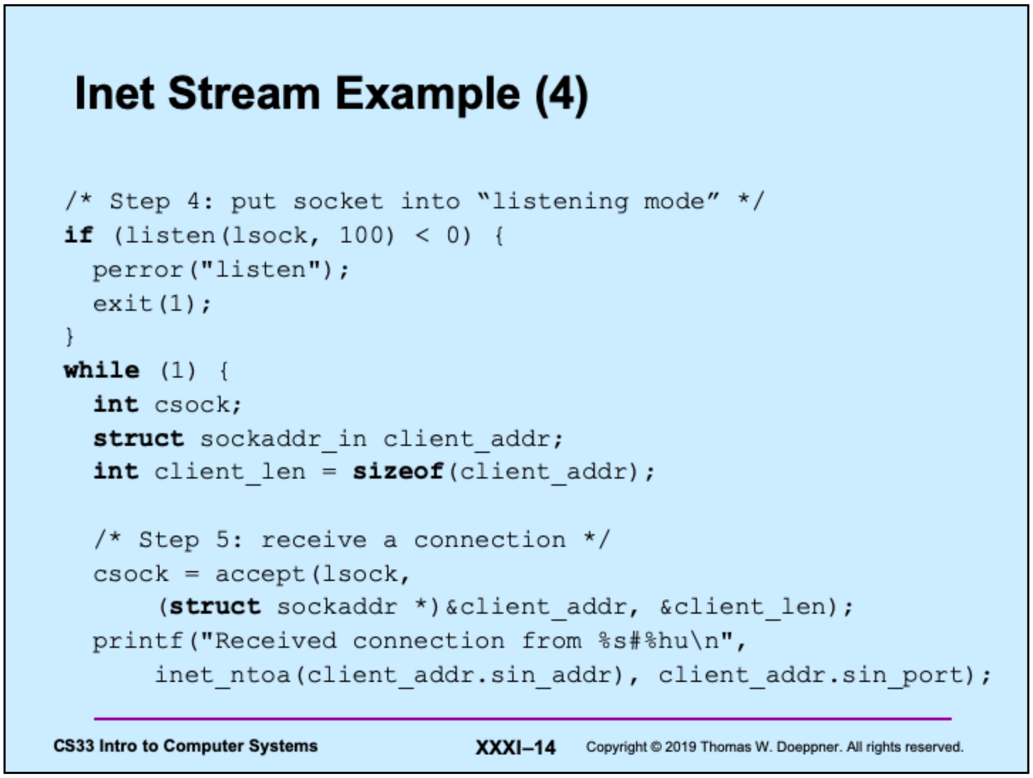
```
// Step 1: establish a socket for TCP
if ((lsock = socket(AF_INET, SOCK_STREAM, 0)) < 0) {
  perror("socket");
  exit(1);
}
```



Inet Stream Example (3)

```
/* Step 2: set up our address */
memset(&my_addr, 0, sizeof(my_addr));
my_addr.sin_family = AF_INET;
my_addr.sin_addr.s_addr = htonl(INADDR_ANY);
my_addr.sin_port = htons(atoi(argv[1]));

/* Step 3: bind the address to our socket */
if (bind(lsock, (struct sockaddr *)&my_addr,
    sizeof(my_addr)) < 0) {
  perror("bind");
  exit(1);
}
```

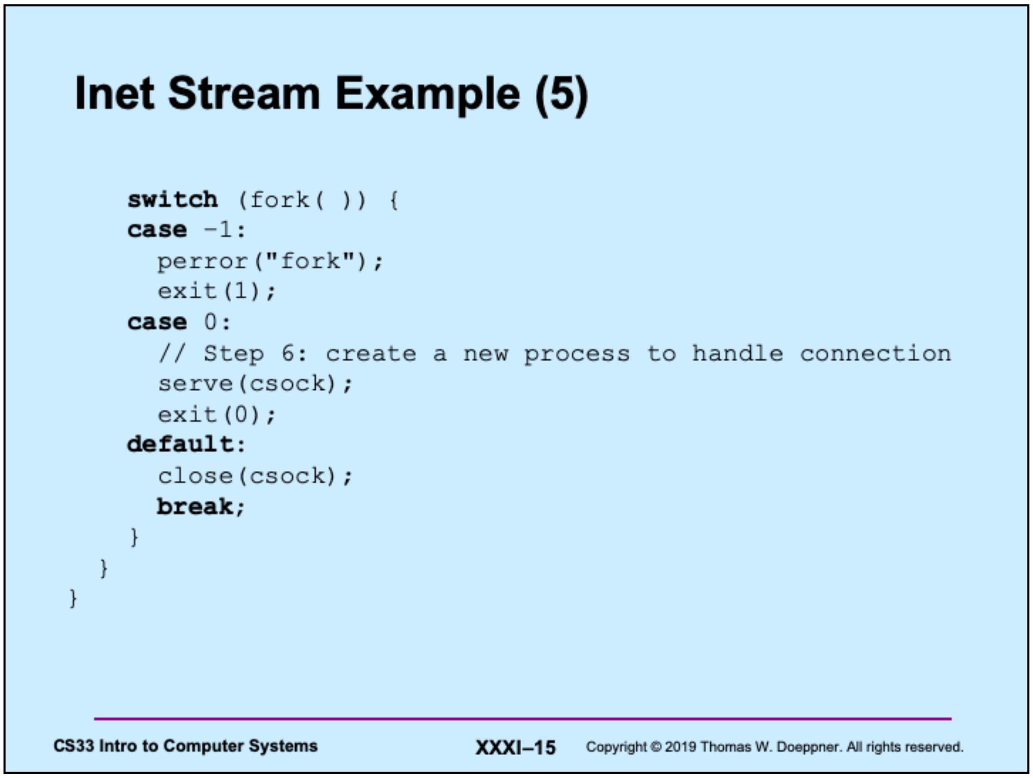
The *memset* command copies some number of instances of its second argument into what its first argument points to. The number of instances is given by its third argument. As used here it is setting *my_addr* to all zeroes.



Inet Stream Example (4)

```
/* Step 4: put socket into “listening mode” */
if (listen(lsock, 100) < 0) {
  perror("listen");
  exit(1);
}
while (1) {
  int csock;
  struct sockaddr_in client_addr;
  int client_len = sizeof(client_addr);

  /* Step 5: receive a connection */
  csock = accept(lsock,
      (struct sockaddr *)&client_addr, &client_len);
  printf("Received connection from %s#%hu\n",
      inet_ntoa(client_addr.sin_addr), client_addr.sin_port);
```

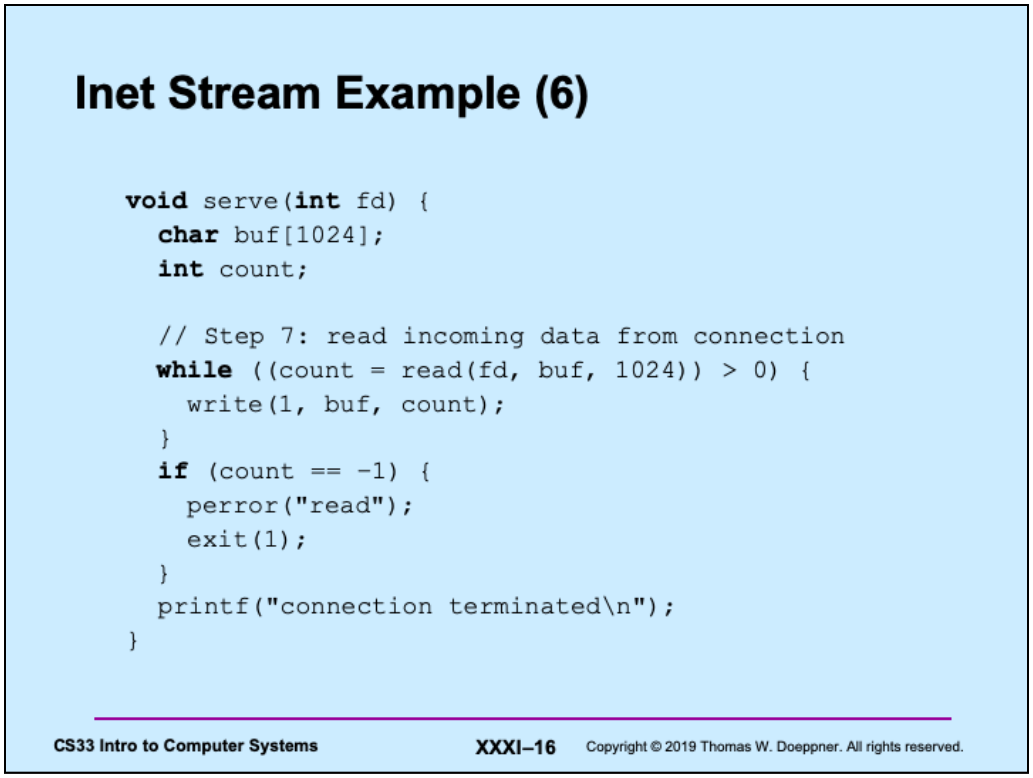
The library routine “inet_ntoa” converts a 32-bit network address into an ASCII string in “dot notation” (bytes are separated by dots).



Inet Stream Example (5)

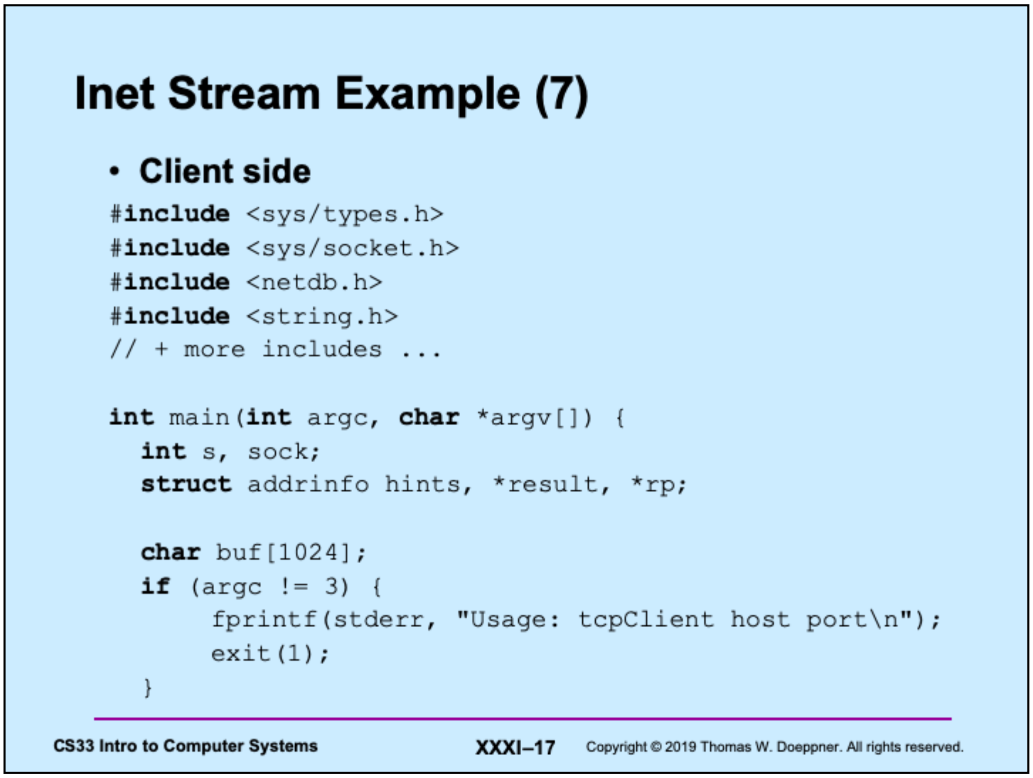
```
    switch (fork( )) {
    case -1:
      perror("fork");
      exit(1);
    case 0:
      // Step 6: create a new process to handle connection
      serve(csock);
      exit(0);
    default:
      close(csock);
      break;
    }
  }
}
```

The server may have any number of clients connecting to it. The approach shown here is for it to spawn a new process each time it gets a new client connection. This new process communicates with the client.



Inet Stream Example (6)

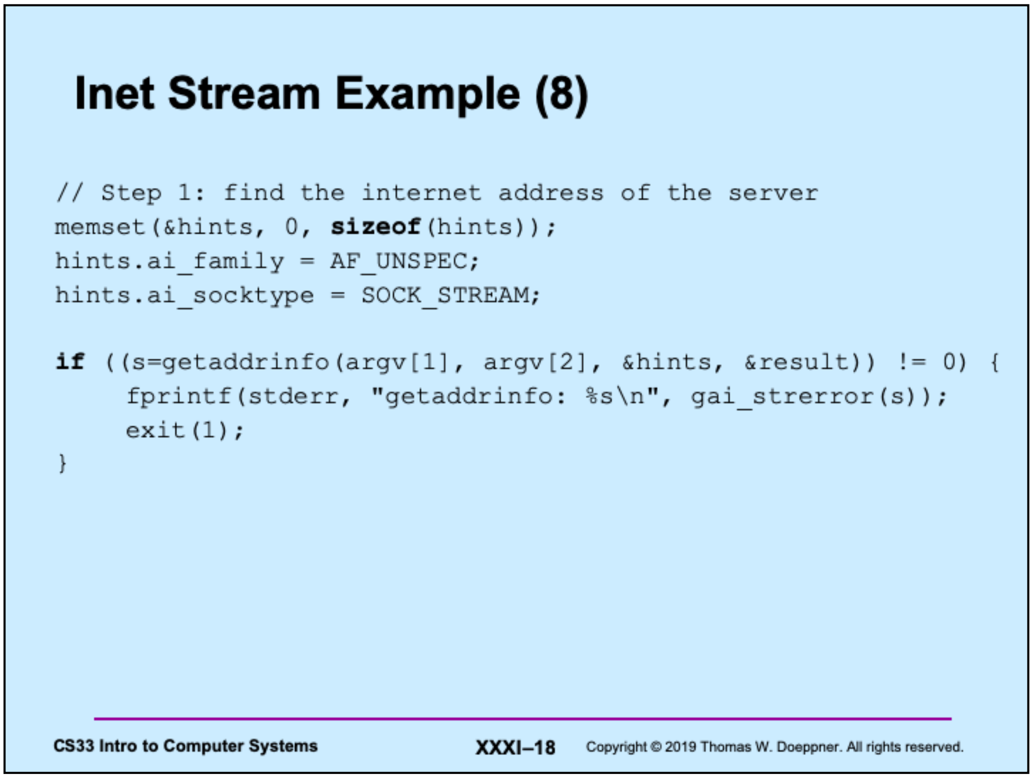
```
void serve(int fd) {
  char buf[1024];
  int count;

  // Step 7: read incoming data from connection
  while ((count = read(fd, buf, 1024)) > 0) {
    write(1, buf, count);
  }
  if (count == -1) {
    perror("read");
    exit(1);
  }
  printf("connection terminated\n");
}
```



Inet Stream Example (7)

- **Client side**

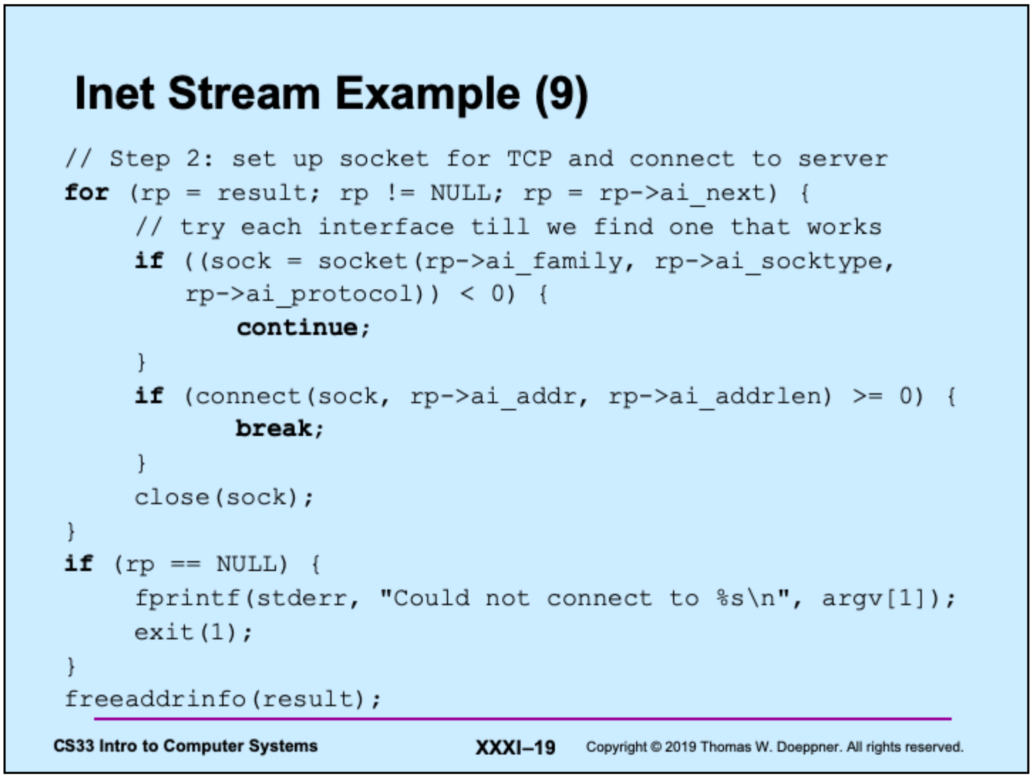
```
#include <sys/types.h>
#include <sys/socket.h>
#include <netdb.h>
#include <string.h>
// + more includes ...

int main(int argc, char *argv[]) {
  int s, sock;
  struct addrinfo hints, *result, *rp;

  char buf[1024];
  if (argc != 3) {
       fprintf(stderr, "Usage: tcpClient host port\n");
       exit(1);
  }
```



Inet Stream Example (8)

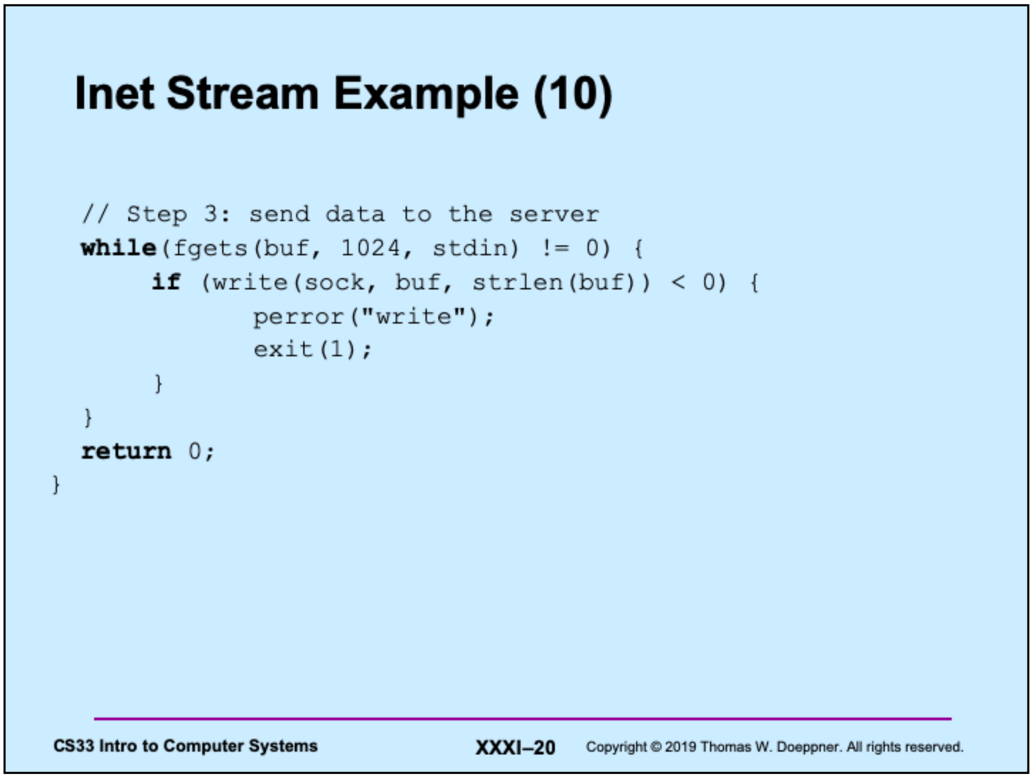
```
// Step 1: find the internet address of the server
memset(&hints, 0, sizeof(hints));
hints.ai_family = AF_UNSPEC;
hints.ai_socktype = SOCK_STREAM;

if ((s=getaddrinfo(argv[1], argv[2], &hints, &result)) != 0) {
     fprintf(stderr, "getaddrinfo: %s\n", gai_strerror(s));
     exit(1);
}
```

We specify AF_UNSPEC for the address family, which allows us to connect to hosts supporting either IPv4 or IPv6.



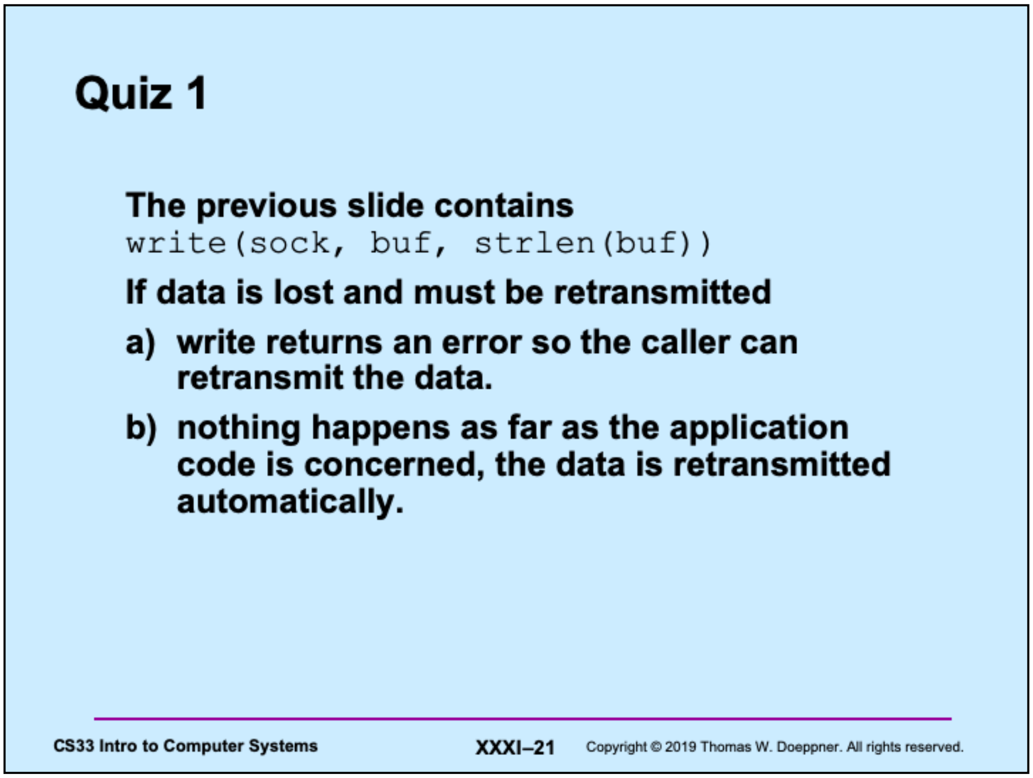
Inet Stream Example (9)

```
// Step 2: set up socket for TCP and connect to server
for (rp = result; rp != NULL; rp = rp->ai_next) {
    // try each interface till we find one that works
    if ((sock = socket(rp->ai_family, rp->ai_socktype,
       rp->ai_protocol)) < 0) {
           continue;
    }
    if (connect(sock, rp->ai_addr, rp->ai_addrlen) >= 0) {
           break;
    }
    close(sock);
}
if (rp == NULL) {
    fprintf(stderr, "Could not connect to %s\n", argv[1]);
    exit(1);
}
freeaddrinfo(result);
```



Inet Stream Example (10)

```
  // Step 3: send data to the server
  while(fgets(buf, 1024, stdin) != 0) {
       if (write(sock, buf, strlen(buf)) < 0) {
              perror("write");
              exit(1);
       }
  }
  return 0;
}
```



Quiz 1

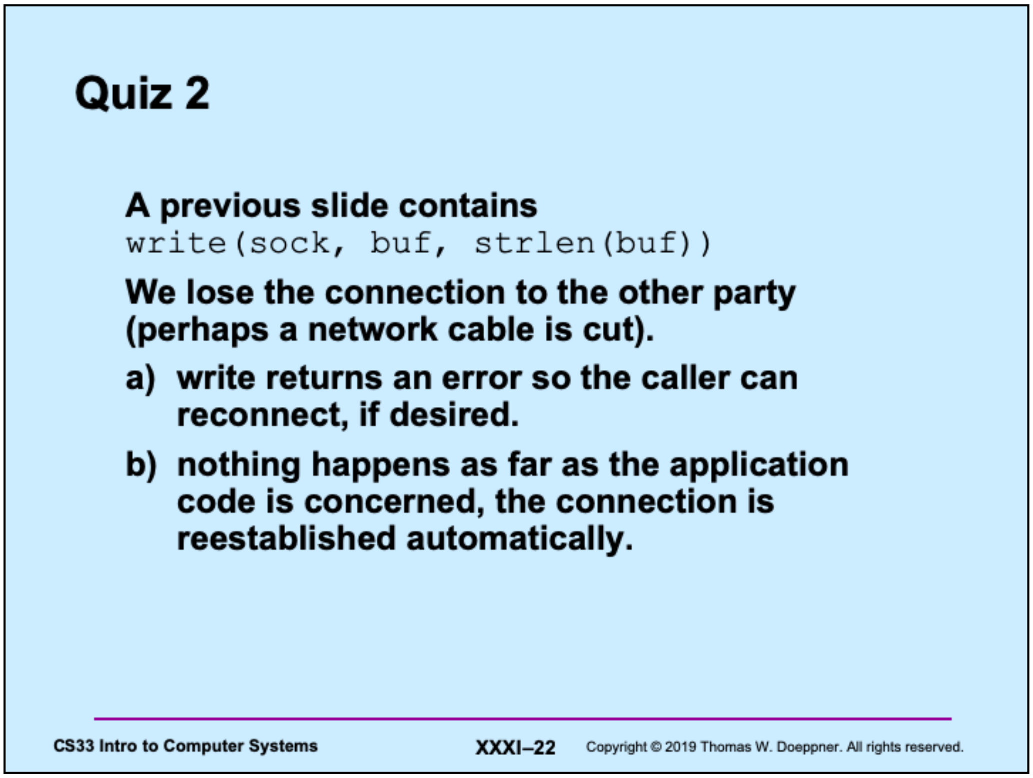
The previous slide contains

```
write(sock, buf, strlen(buf))
```

If data is lost and must be retransmitted

a) write returns an error so the caller can retransmit the data.

b) nothing happens as far as the application code is concerned, the data is retransmitted automatically.



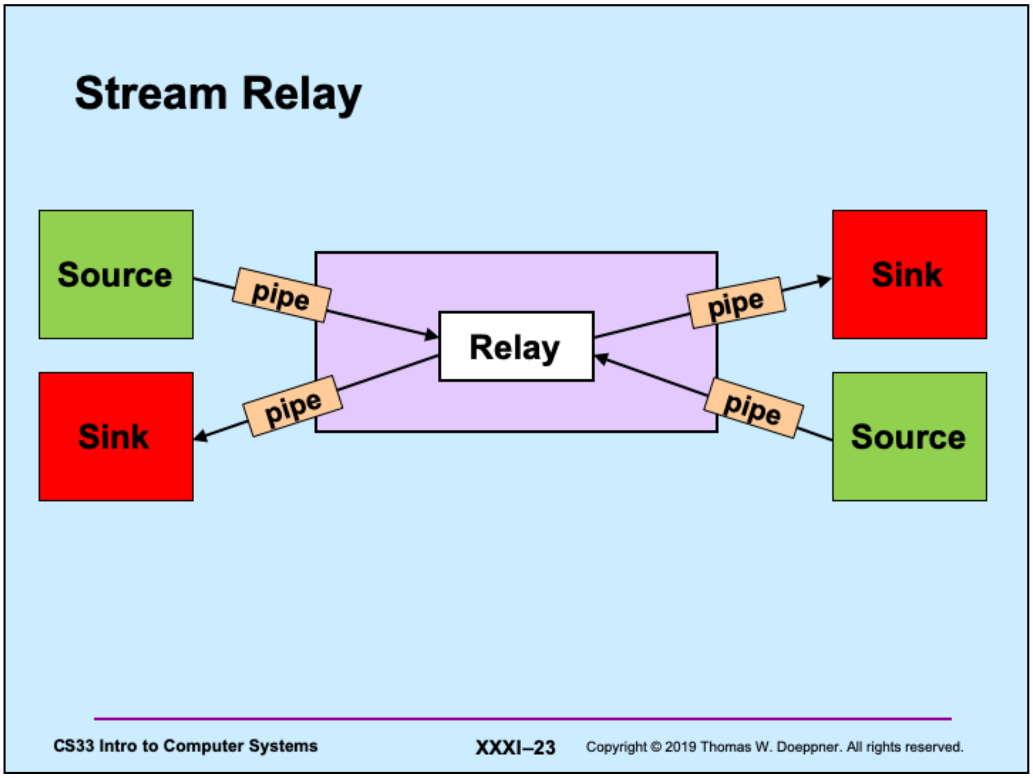
Quiz 2

A previous slide contains
`write(sock, buf, strlen(buf))`

We lose the connection to the other party (perhaps a network cable is cut).

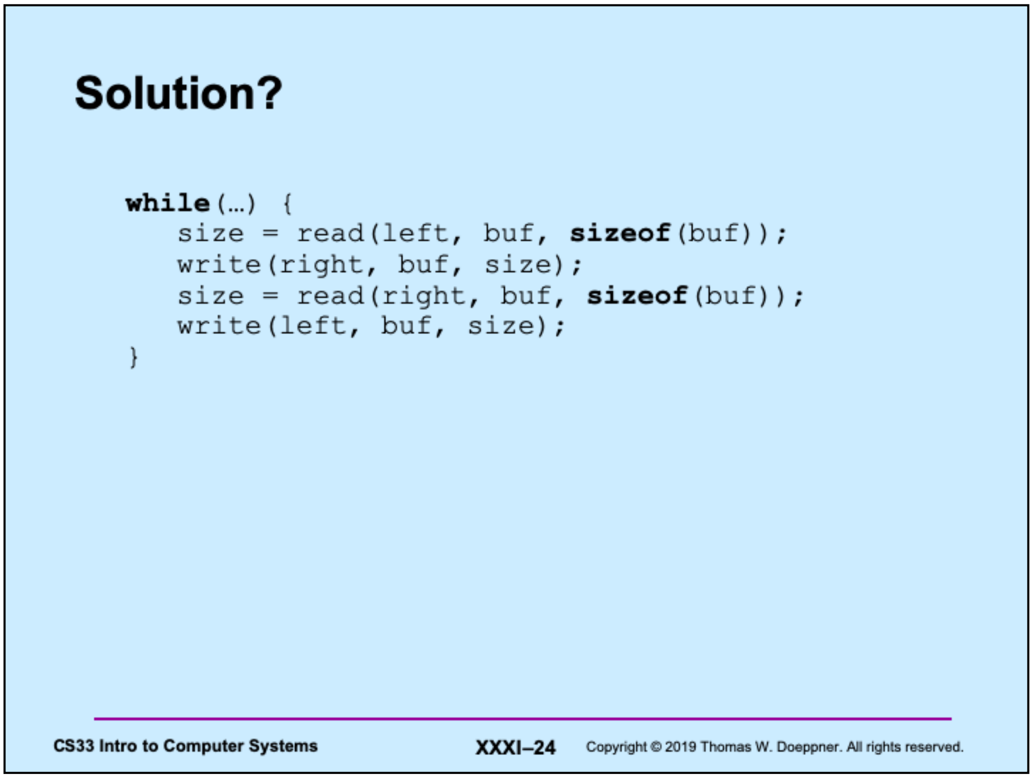
a) write returns an error so the caller can reconnect, if desired.

b) nothing happens as far as the application code is concerned, the connection is reestablished automatically.



Stream Relay

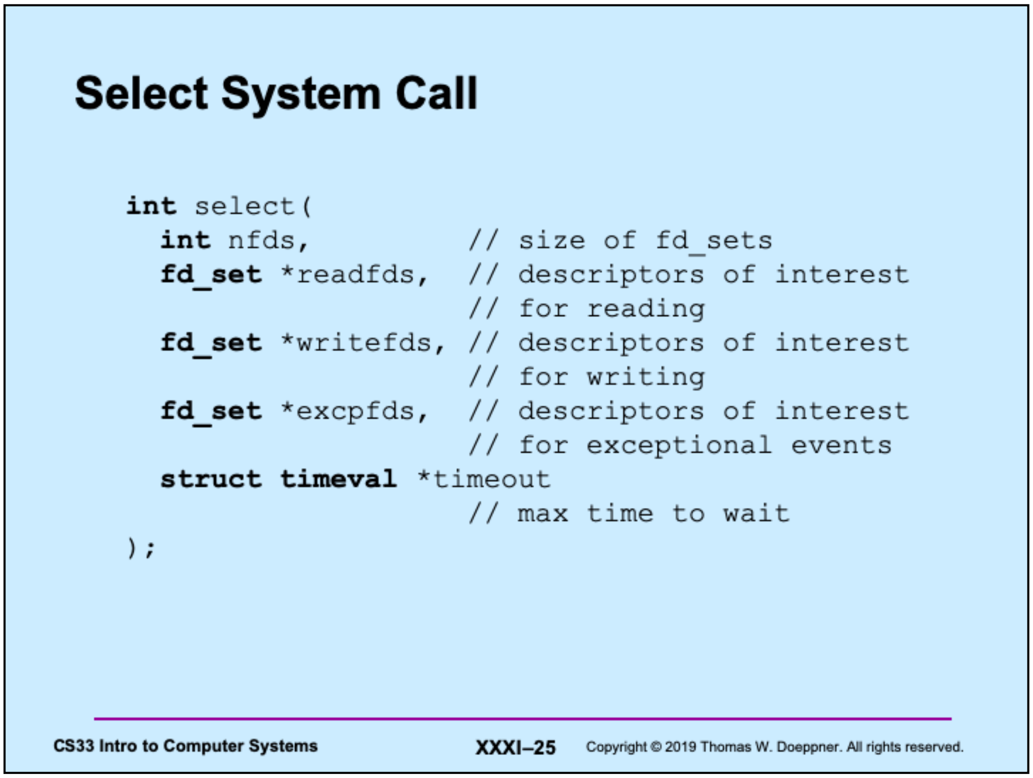
We start by looking at what's known as *event-based programming*: we write code that responds to events coming from a number of sources. As a simple example, before we use the approach in a networking example, we exam a simple relay: we want to write a program that takes data, via a pipe, from the left source and sends it, via a pipe, to the right sink. At the same time it takes data from the right source and sends it to the left sink.



Solution?

```
while(…) {
   size = read(left, buf, sizeof(buf));
   write(right, buf, size);
   size = read(right, buf, sizeof(buf));
   write(left, buf, size);
}
```

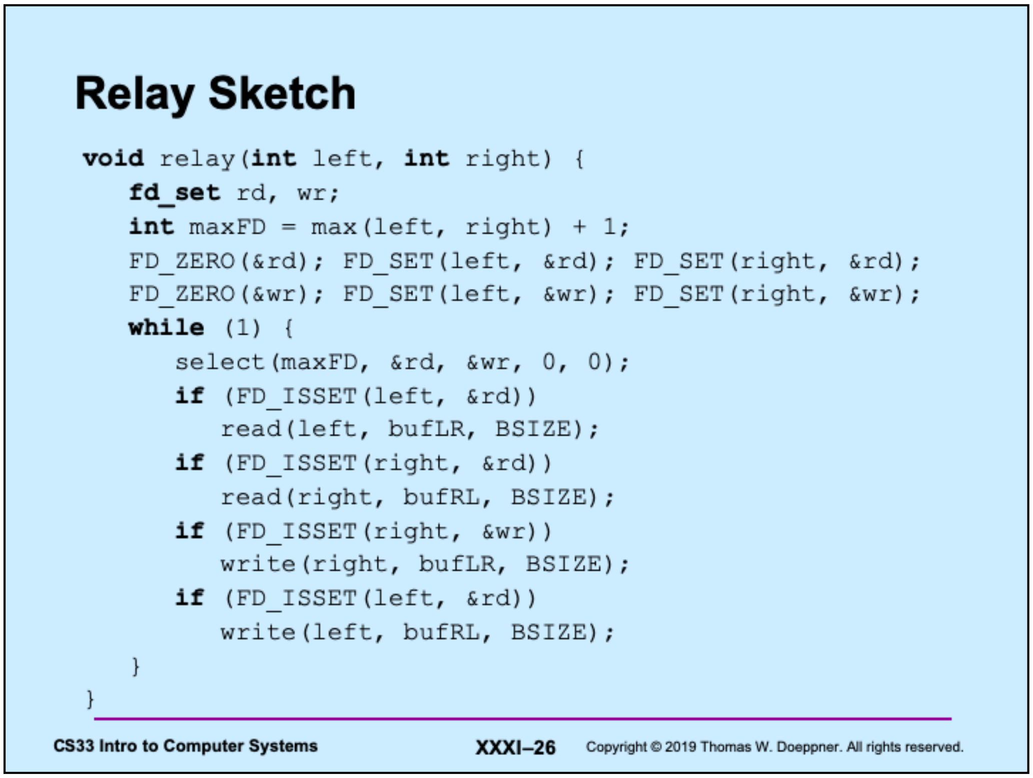
This solution is probably not what we’d want, since it strictly alternates between processing the data stream in one direction and then the other.



Select System Call

```
int select(
  int nfds,          // size of fd_sets
  fd_set *readfds,   // descriptors of interest
                     // for reading
  fd_set *writefds,  // descriptors of interest
                     // for writing
  fd_set *excpfds,   // descriptors of interest
                     // for exceptional events
  struct timeval *timeout
                     // max time to wait
);
```

The select system call operates on three sets of file descriptors: one of fie descriptors we're interested in reading from, one of file descriptors we're interested in writing to, and one of file descriptors that might have exceptional conditions pending (we haven't covered any examples of such things – they come up as a peculiar feature of TCP known as out-of-band data, which is beyond the scope of this course). A call to select waits until at least one of the file descriptors in the given sets has something of interest. In particular, for a file descriptor in the read set, it's possible to read data from it; for a file descriptor in the write set, it's possible to write data to it. The nfds parameter indicates the maximum file descriptor number in any of the sets. The timeout parameter may be used to limit how long select waits. If set to zero, select waits indefinitely.



Relay Sketch

```
void relay(int left, int right) {
   fd_set rd, wr;
   int maxFD = max(left, right) + 1;
   FD_ZERO(&rd); FD_SET(left, &rd); FD_SET(right, &rd);
   FD_ZERO(&wr); FD_SET(left, &wr); FD_SET(right, &wr);
   while (1) {
      select(maxFD, &rd, &wr, 0, 0);
      if (FD_ISSET(left, &rd))
         read(left, bufLR, BSIZE);
      if (FD_ISSET(right, &rd))
         read(right, bufRL, BSIZE);
      if (FD_ISSET(right, &wr))
         write(right, bufLR, BSIZE);
      if (FD_ISSET(left, &rd))
         write(left, bufRL, BSIZE);
   }
}
```

Here a simplified version of a program to handle the relay problem using *select*. An *fd_set* is a data type that represents a set of file descriptors. FD_ZERO, FD_SET, and FD_ISSET are macros for working with fd_sets; the first makes such a set represent the null set, the second sets a particular file descriptor to included in the set, the last checks to see if a particular file descriptor is included in the set.

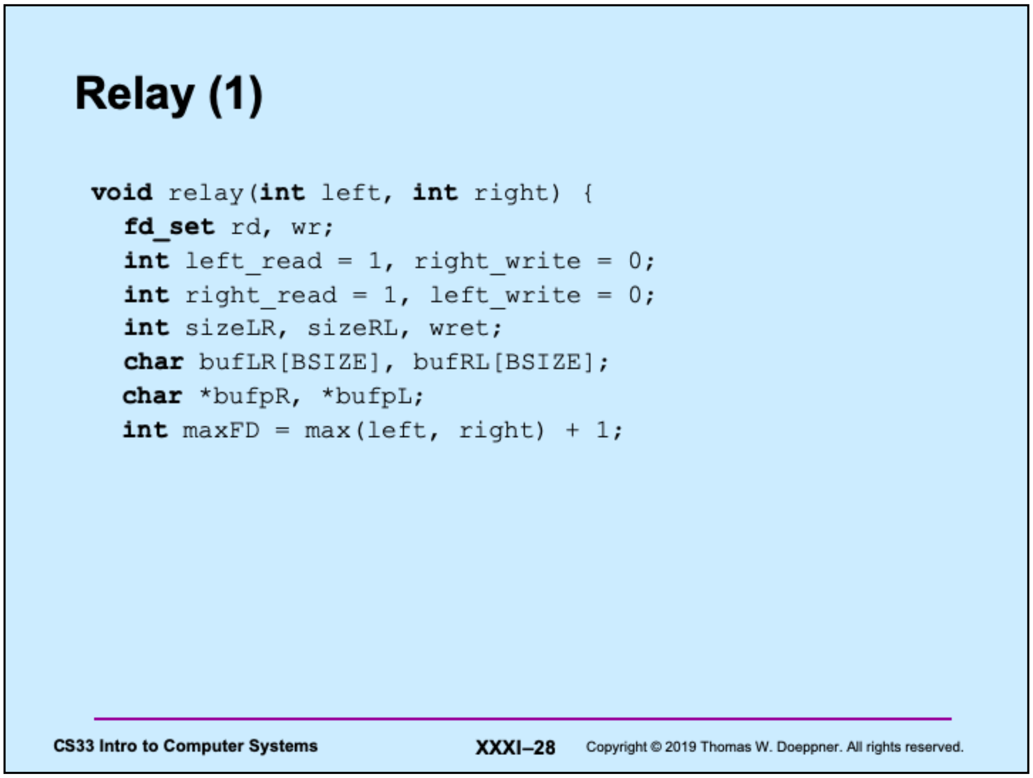
Quiz 3

40 bytes have been read from the left-hand source. Select reports that it is ok to write to the right-hand sink.

a) You’re guaranteed you can immediately write all 40 bytes to the right-hand sink

b) All that’s guaranteed is that you can immediately write at least one byte to the right-hand sink

c) Nothing is guaranteed

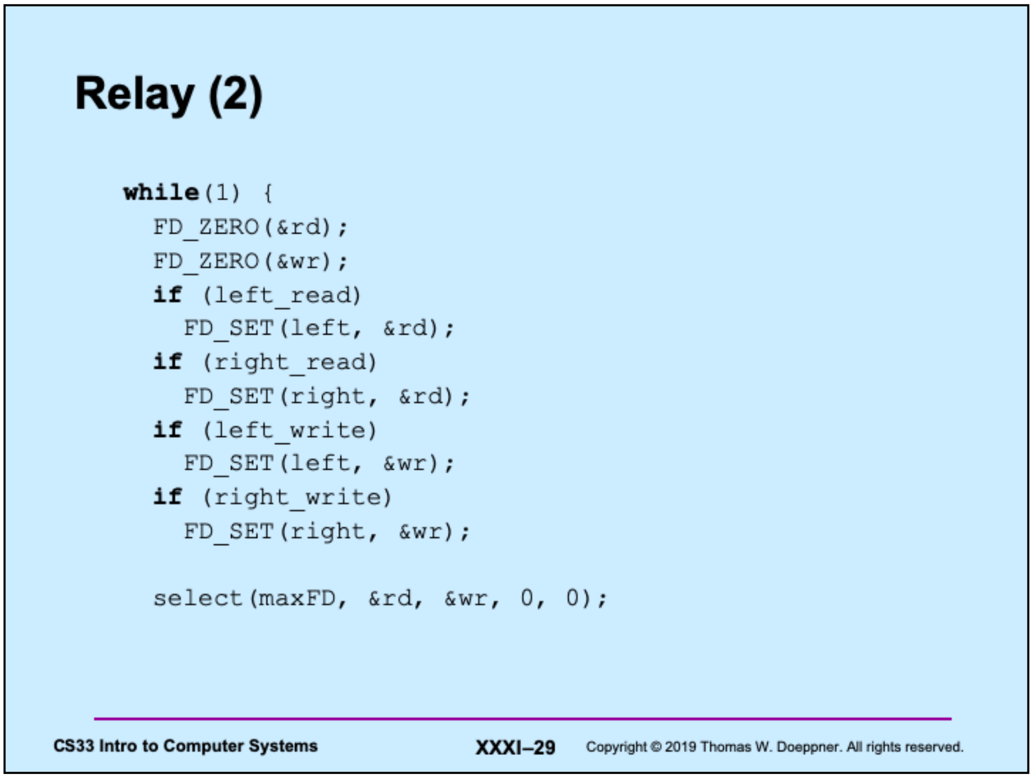


Relay (1)

```
void relay(int left, int right) {
  fd_set rd, wr;
  int left_read = 1, right_write = 0;
  int right_read = 1, left_write = 0;
  int sizeLR, sizeRL, wret;
  char bufLR[BSIZE], bufRL[BSIZE];
  char *bufpR, *bufpL;
  int maxFD = max(left, right) + 1;
```

This and the next three slides give a more complete version of the relay program.

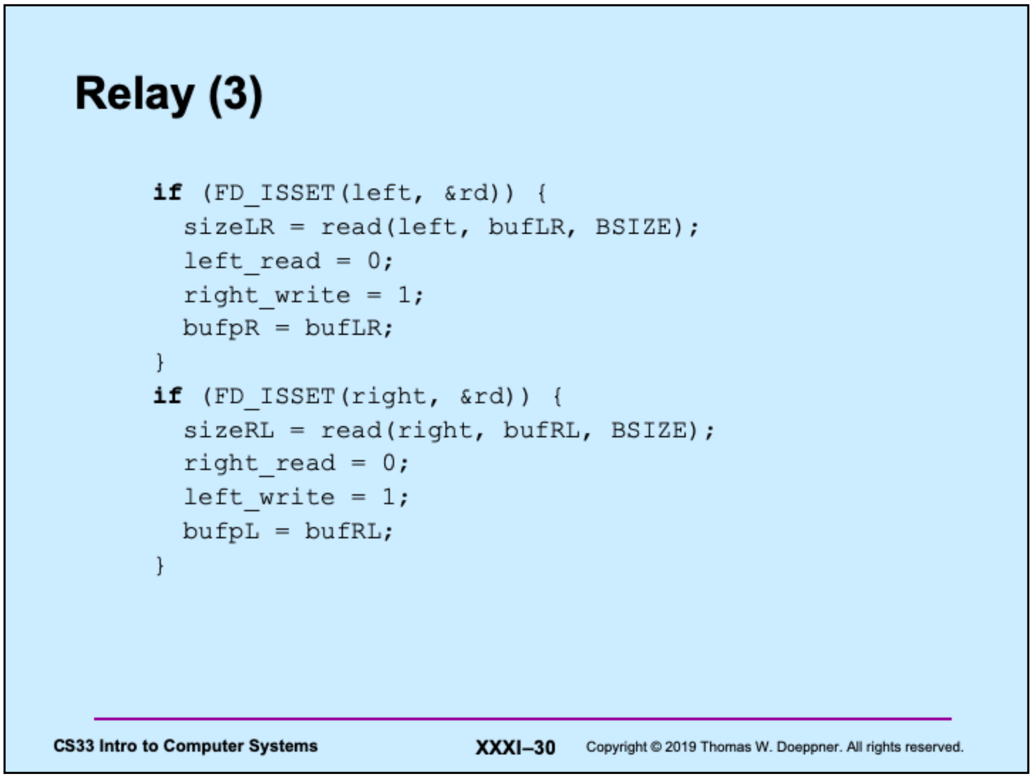
Initially our program is prepared to read from either the left or the right side, but it's not prepared to write, since it doesn't have anything to write. The variables *left_read* and *right_read* are set to one to indicate that we want to read from the left and right sides. The variables *right_write* and *left_write* are set to zero to indicate that we don't yet want to write to either side.



Relay (2)

```
while(1) {
  FD_ZERO(&rd);
  FD_ZERO(&wr);
  if (left_read)
    FD_SET(left, &rd);
  if (right_read)
    FD_SET(right, &rd);
  if (left_write)
    FD_SET(left, &wr);
  if (right_write)
    FD_SET(right, &wr);

  select(maxFD, &rd, &wr, 0, 0);
```

We set up the fd_sets *rd* and *wr* to indicate what we are interested in reading from and writing to (initially we have no interest in writing, but are interested in reading from either side).

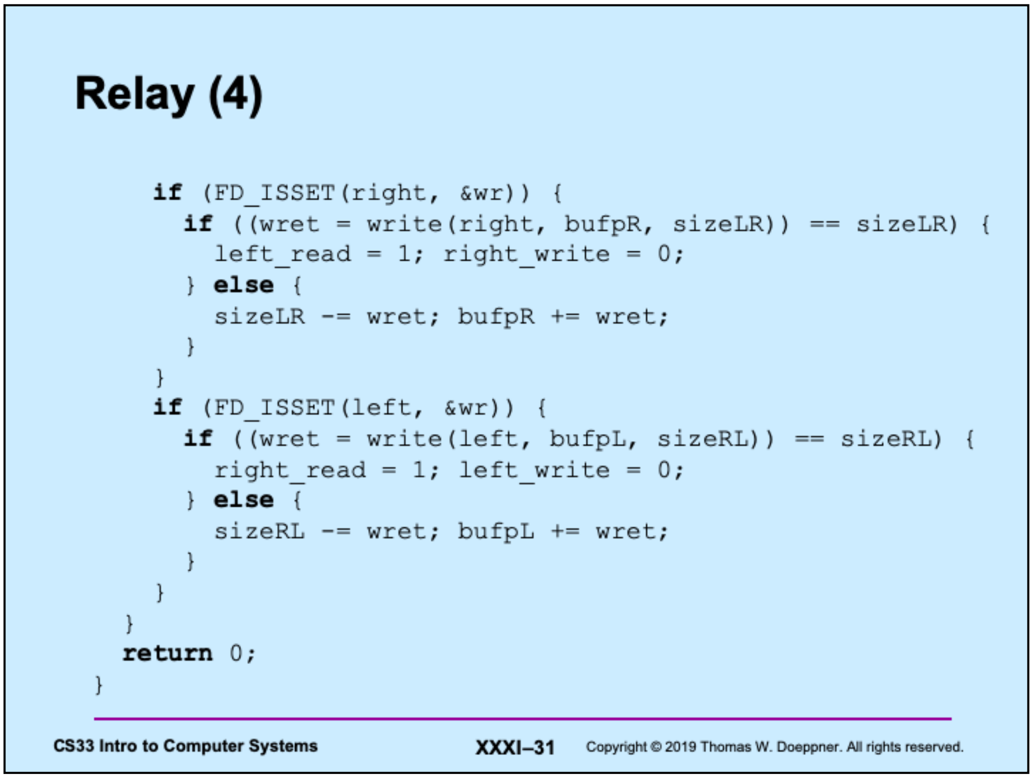


Relay (3)

```
if (FD_ISSET(left, &rd)) {
  sizeLR = read(left, bufLR, BSIZE);
  left_read = 0;
  right_write = 1;
  bufpR = bufLR;
}
if (FD_ISSET(right, &rd)) {
  sizeRL = read(right, bufRL, BSIZE);
  right_read = 0;
  left_write = 1;
  bufpL = bufRL;
}
```

If there is something to read from the left side, we read it. Having read it, we’re temporarily not interested in reading anything further from the left side, but now want to write to the right side.

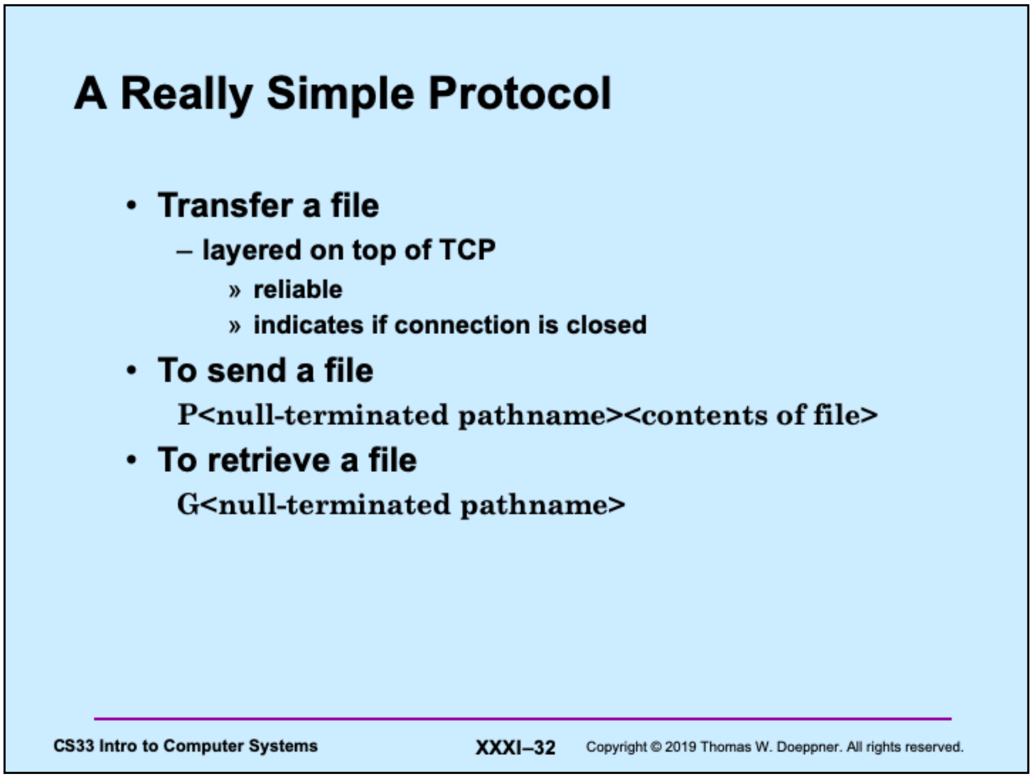
In a similar fashion, if there is something to read from the right side, we read it.



Relay (4)

```
    if (FD_ISSET(right, &wr)) {
      if ((wret = write(right, bufpR, sizeLR)) == sizeLR) {
        left_read = 1; right_write = 0;
      } else {
        sizeLR -= wret; bufpR += wret;
      }
    }
    if (FD_ISSET(left, &wr)) {
      if ((wret = write(left, bufpL, sizeRL)) == sizeRL) {
        right_read = 1; left_write = 0;
      } else {
        sizeRL -= wret; bufpL += wret;
      }
    }
  }
  return 0;
}
```

Writing is a bit more complicated, since the outgoing pipe might not have room for everything we have to write, but just some of it. Thus we must pay attention to what write returns. If everything has been written, then we can go back to reading from the other side, but if not, we continue trying to write.



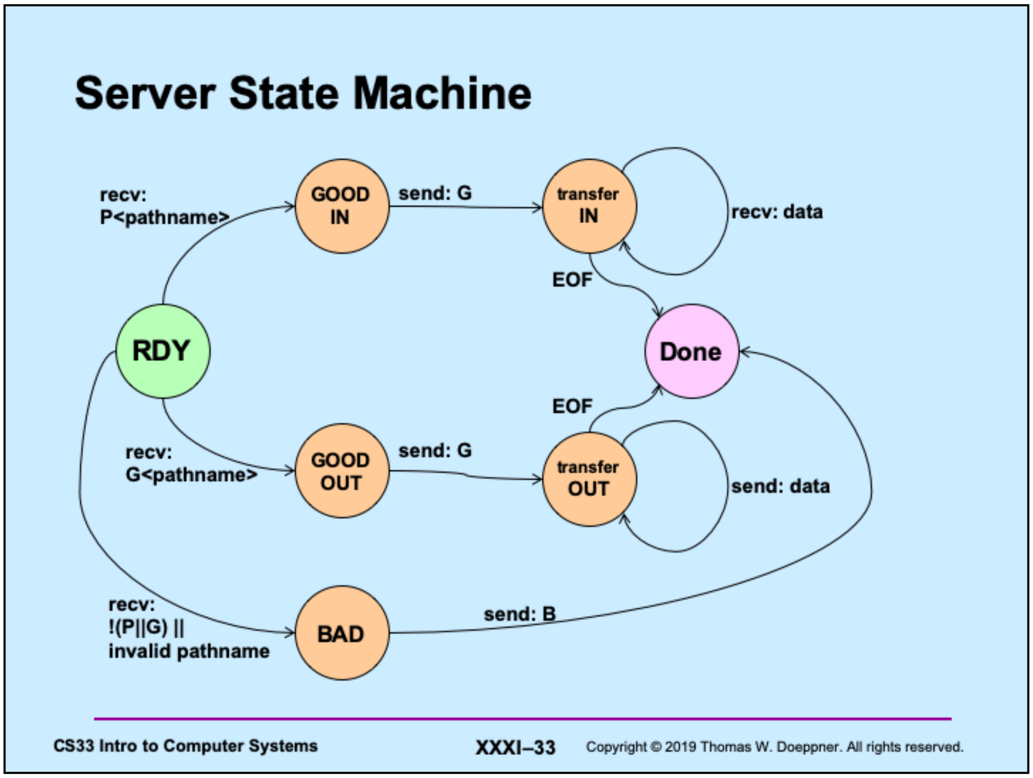
A Really Simple Protocol

- Transfer a file
  - layered on top of TCP
    - » reliable
    - » indicates if connection is closed
- To send a file

  P<null-terminated pathname><contents of file>
- To retrieve a file

  G<null-terminated pathname>

Now we use the event paradigm to implement a simple file-transfer program.



Server State Machine

RDY

recv:
P<pathname>

GOOD IN

send: G

transfer IN

recv: data

EOF

Done

recv:
G<pathname>

GOOD OUT

send: G

transfer OUT

send: data

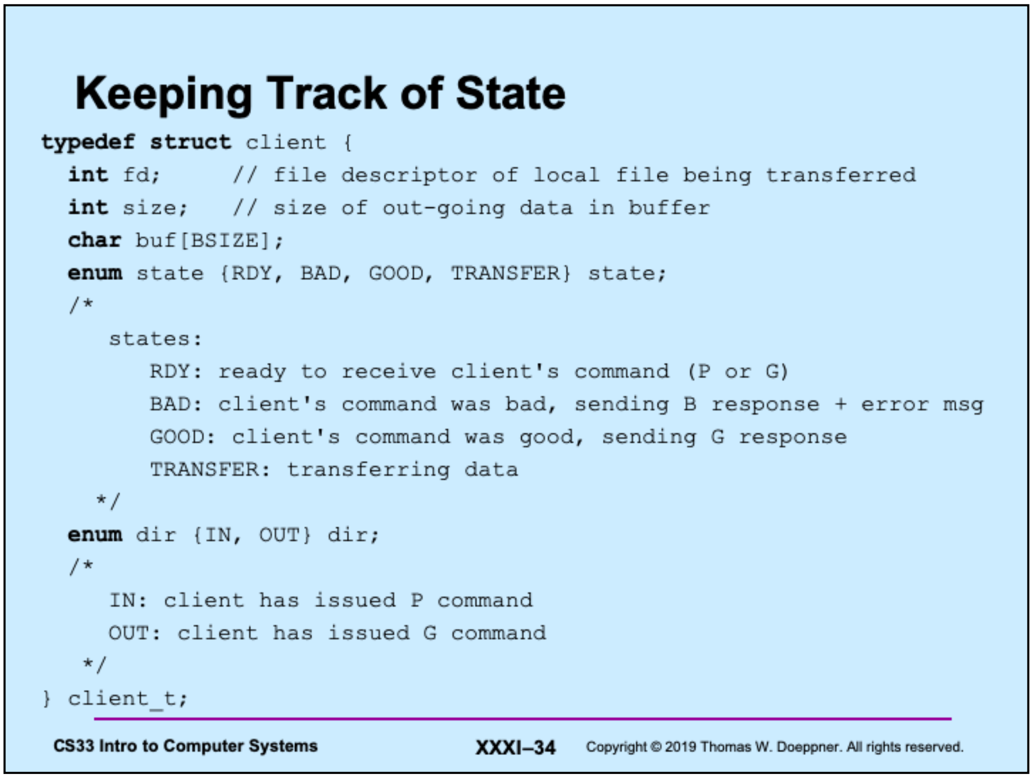
EOF

recv:
!(P||G) ||
invalid pathname

BAD

send: B

We design the protocol in terms of a simple state machine. The server will be dealing concurrently with many clients and will maintain a state machine for each client.

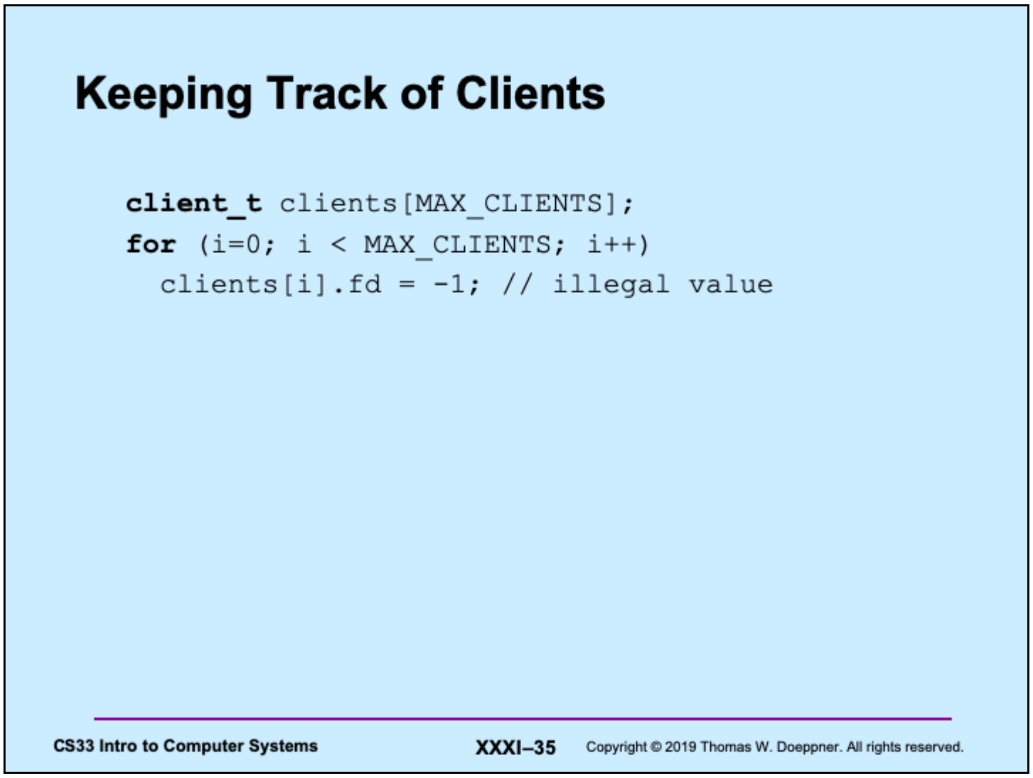


Keeping Track of State

```
typedef struct client {
  int fd;     // file descriptor of local file being transferred
  int size;   // size of out-going data in buffer
  char buf[BSIZE];
  enum state {RDY, BAD, GOOD, TRANSFER} state;
  /*
     states:
        RDY: ready to receive client's command (P or G)
        BAD: client's command was bad, sending B response + error msg
        GOOD: client's command was good, sending G response
        TRANSFER: transferring data
    */
  enum dir {IN, OUT} dir;
  /*
     IN: client has issued P command
     OUT: client has issued G command
   */
} client_t;
```

Note the use of the *enum* data type. Variables of this type have a finite set of possible values, as given in the declaration.

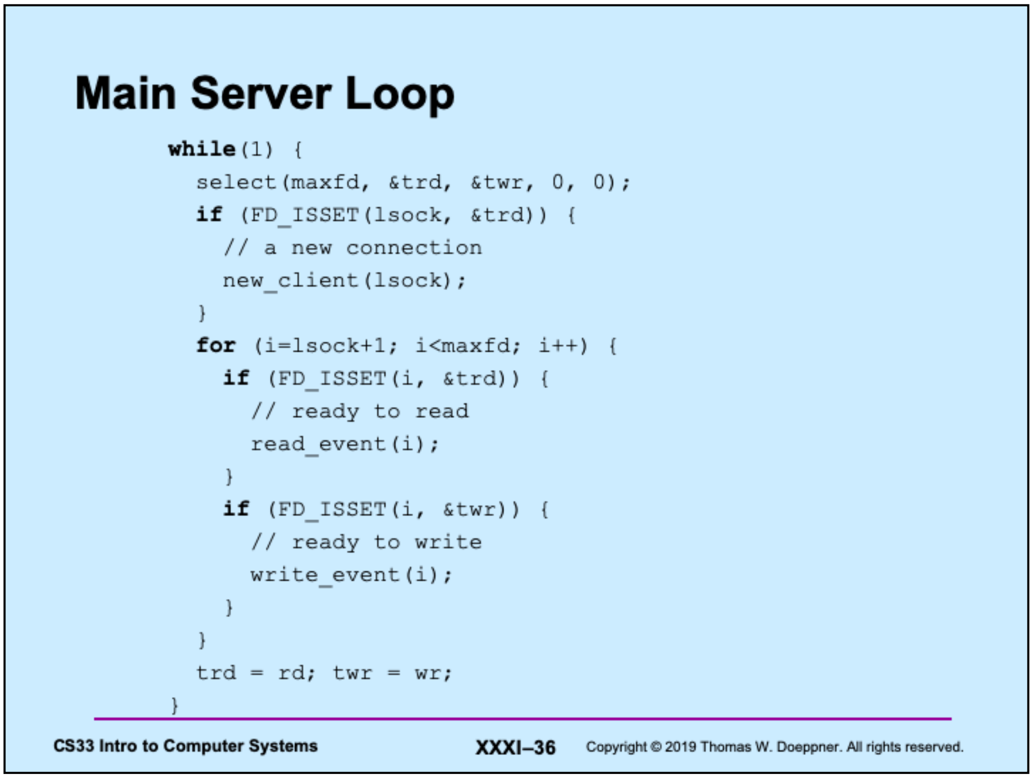
Rather than have separate GOOD-IN, GOOD-OUT, TRANSFER-IN, and TRANSFER-OUT states, we have two state variables, one which keeps track of the direction.



Keeping Track of Clients

```
client_t clients[MAX_CLIENTS];
for (i=0; i < MAX_CLIENTS; i++)
  clients[i].fd = -1; // illegal value
```

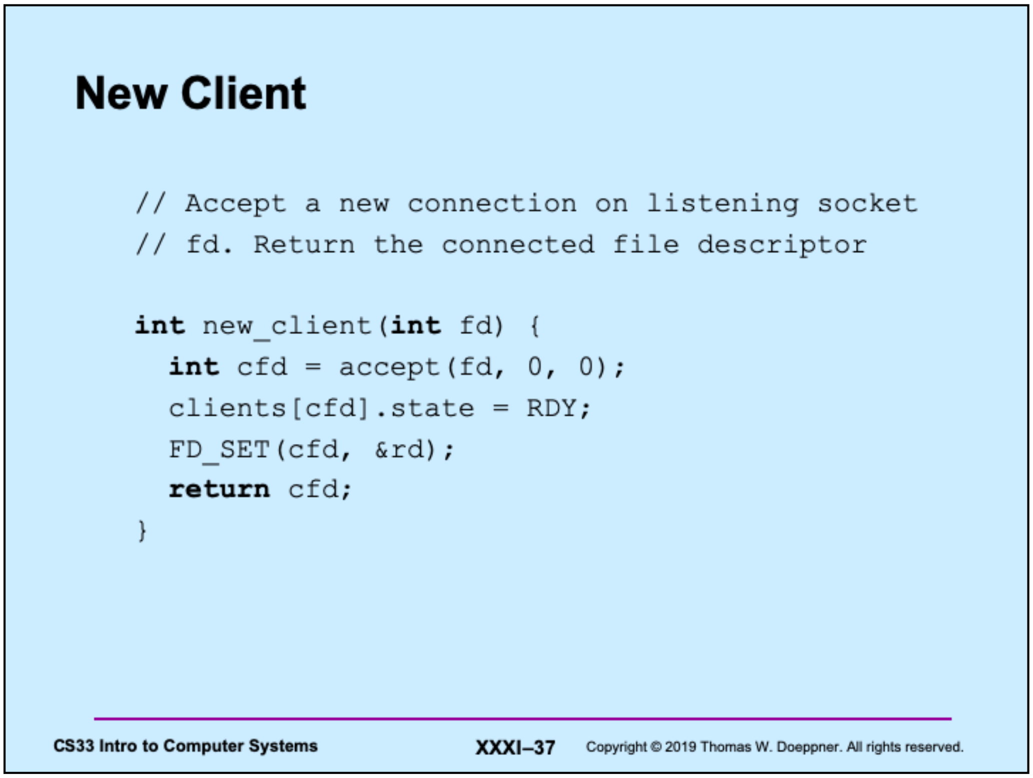
Each client of our server is represented by a separate *client_t* structure. We allocate an array of them and will refer to client's *client_t* structure by the file descriptor of the socket used to communicate with it. Thus if we're using a socket whose file descriptor is *sfd* to communicate with a client, then the client's state is in *clients[sfd]*.



Main Server Loop

```
while(1) {
  select(maxfd, &trd, &twr, 0, 0);
  if (FD_ISSET(lsock, &trd)) {
    // a new connection
    new_client(lsock);
  }
  for (i=lsock+1; i<maxfd; i++) {
    if (FD_ISSET(i, &trd)) {
      // ready to read
      read_event(i);
    }
    if (FD_ISSET(i, &twr)) {
      // ready to write
      write_event(i);
    }
  }
  trd = rd; twr = wr;
}
```

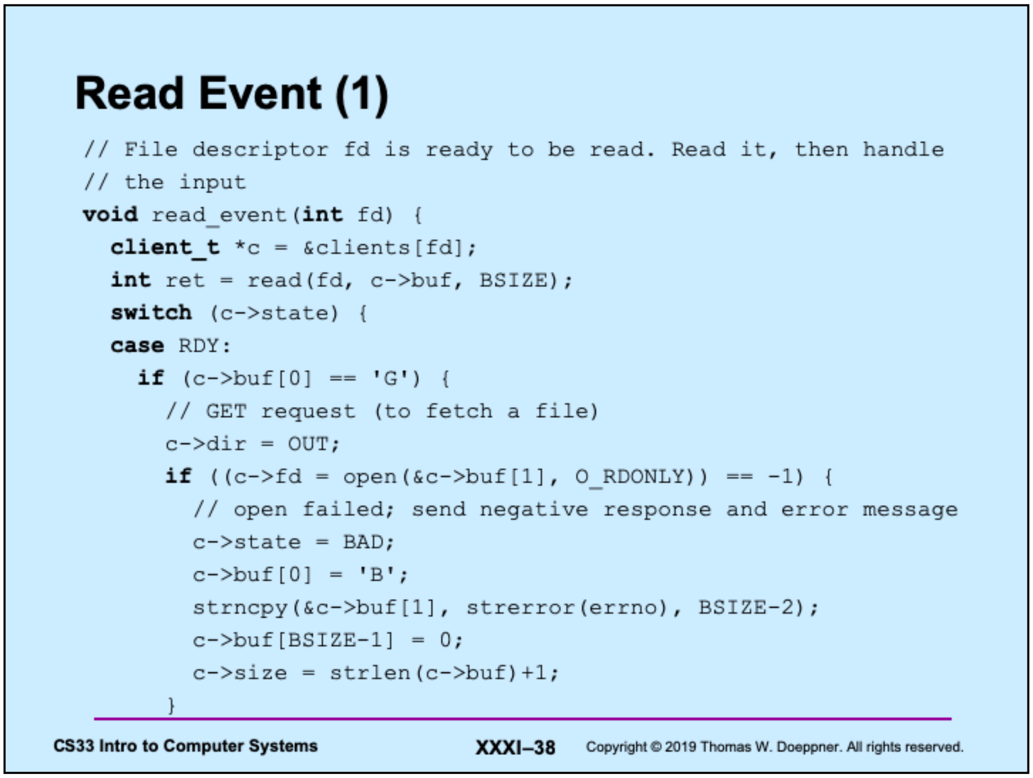
lsock is the file descriptor for the “listening-mode” socket on which the server is waiting for connections. Our server may be handling multiple clients; each will be communicating with the server via a separate connected socket. These sockets have file descriptors greater than *lsock*. Note that *trd*, *twr*, *rd* and *wr* are all of type *fd_set*. *rd* and *wr* are initialized so that *rd* contains just the file descriptor for the listening socket and *wr* is empty. *trd* and *twr* are copied from *rd* and *wr* respectively before the loop is entered. *rd* and *wr* are global variables that are modified by *new_client*, *read_event*, and *write_event*.



New Client

```
// Accept a new connection on listening socket
// fd. Return the connected file descriptor

int new_client(int fd) {
  int cfd = accept(fd, 0, 0);
  clients[cfd].state = RDY;
  FD_SET(cfd, &rd);
  return cfd;
}
```

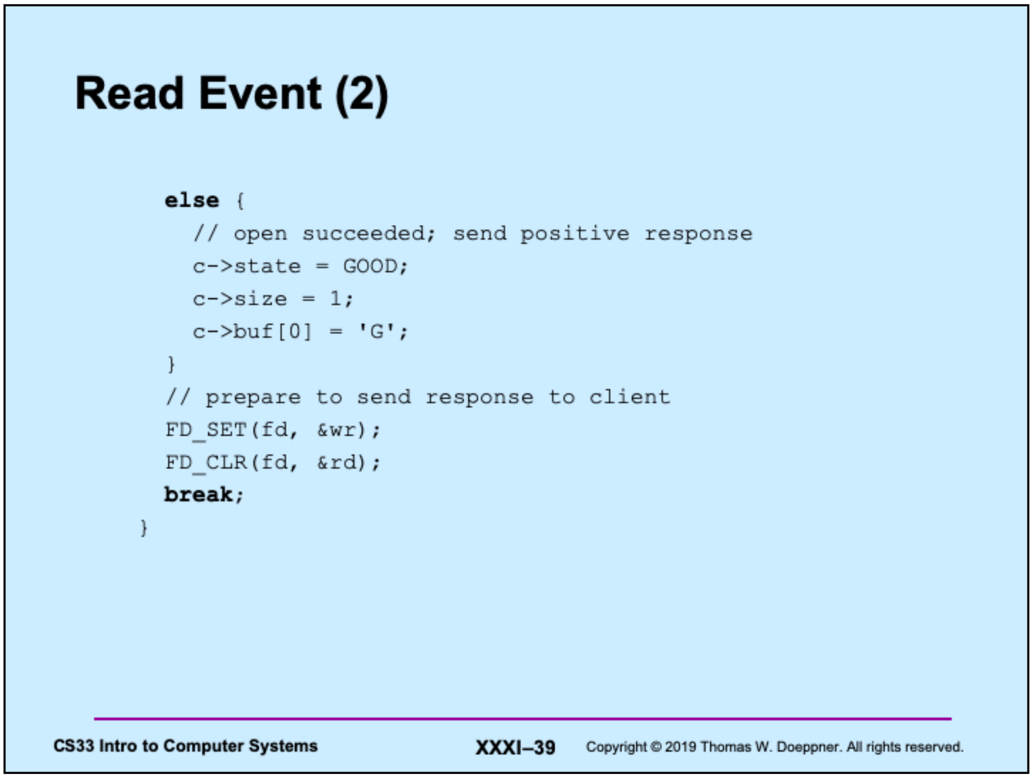
When the server gets a new client, the state machine for that client is initialized in the RDY state, and the file descriptor for the socket used to communicate with the client is added to the set of read file descriptors.



Read Event (1)

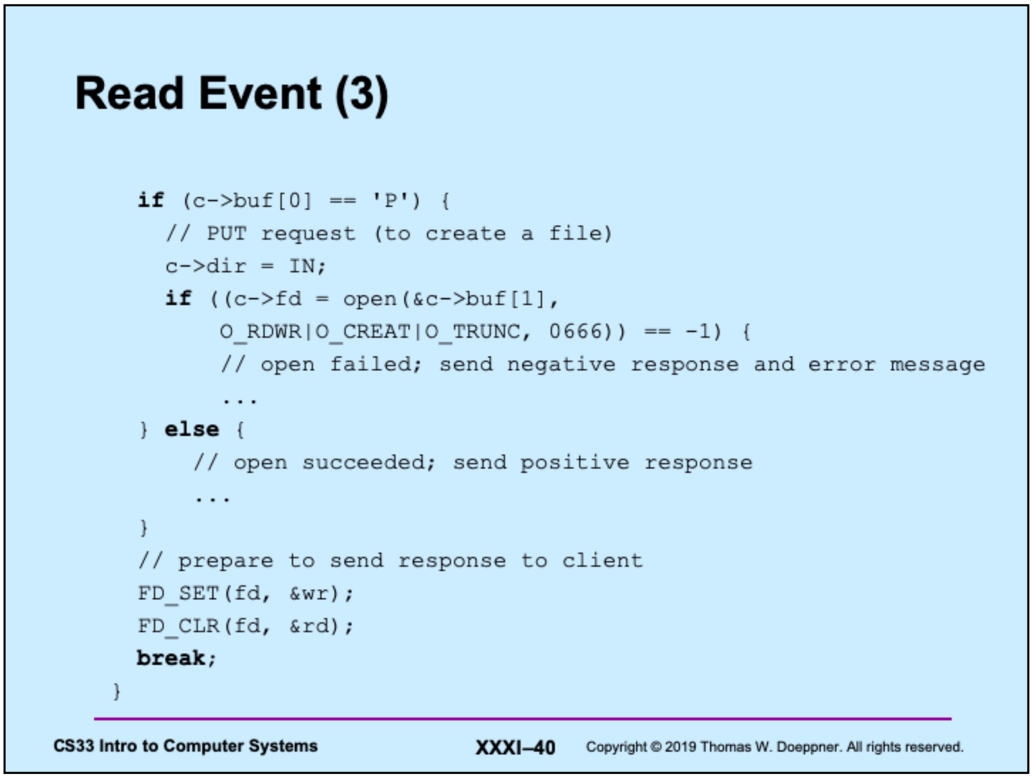
```
// File descriptor fd is ready to be read. Read it, then handle
// the input
void read_event(int fd) {
  client_t *c = &clients[fd];
  int ret = read(fd, c->buf, BSIZE);
  switch (c->state) {
  case RDY:
    if (c->buf[0] == 'G') {
      // GET request (to fetch a file)
      c->dir = OUT;
      if ((c->fd = open(&c->buf[1], O_RDONLY)) == -1) {
        // open failed; send negative response and error message
        c->state = BAD;
        c->buf[0] = 'B';
        strncpy(&c->buf[1], strerror(errno), BSIZE-2);
        c->buf[BSIZE-1] = 0;
        c->size = strlen(c->buf)+1;
      }
```

When the server gets a read event, the file descriptor causing it is used to identify the client. What happens next depends on the state of the client.



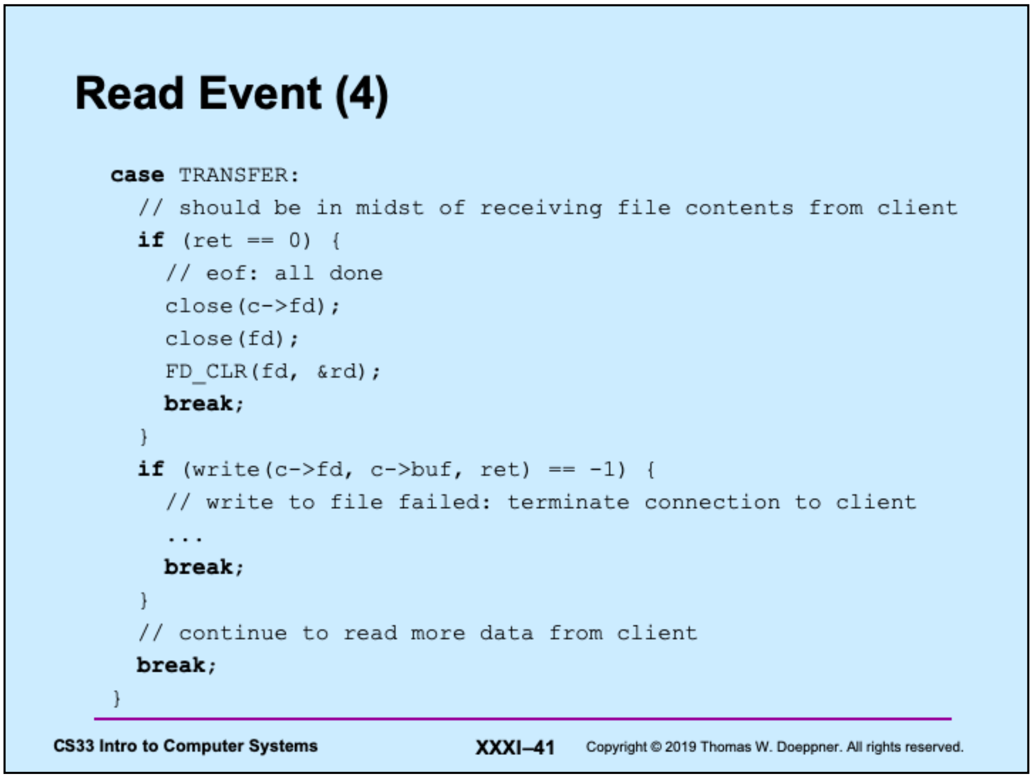
Read Event (2)

```
  else {
    // open succeeded; send positive response
    c->state = GOOD;
    c->size = 1;
    c->buf[0] = 'G';
  }
  // prepare to send response to client
  FD_SET(fd, &wr);
  FD_CLR(fd, &rd);
  break;
}
```



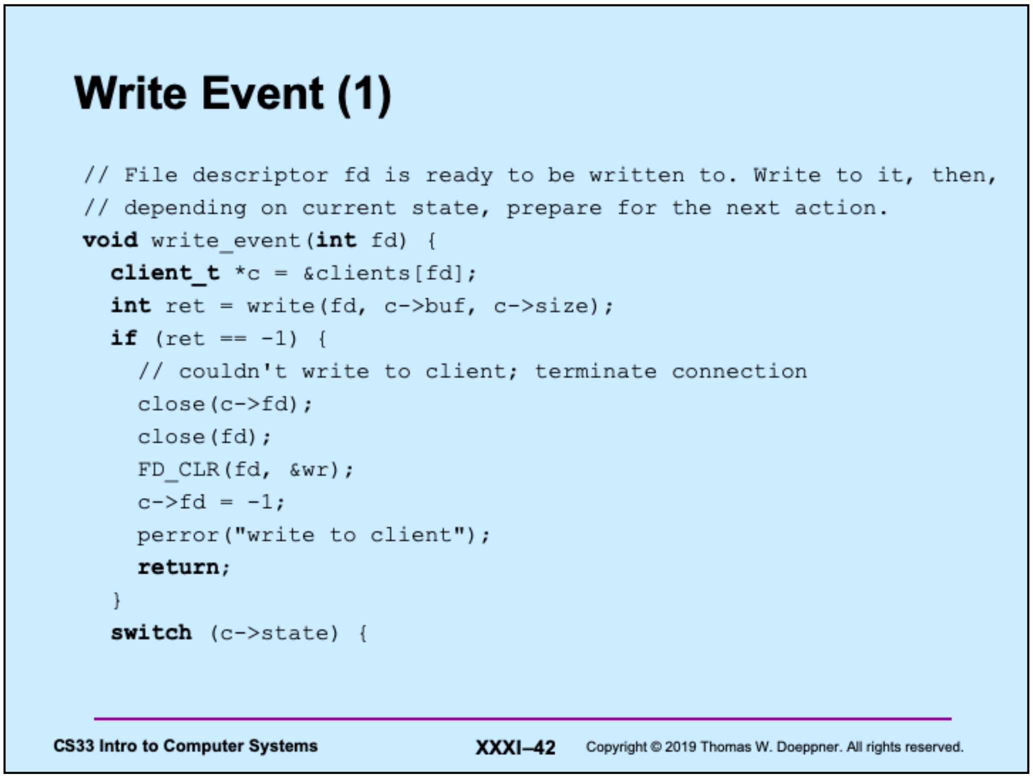
Read Event (3)

```
  if (c->buf[0] == 'P') {
    // PUT request (to create a file)
    c->dir = IN;
    if ((c->fd = open(&c->buf[1],
        O_RDWR|O_CREAT|O_TRUNC, 0666)) == -1) {
        // open failed; send negative response and error message
        ...
  } else {
      // open succeeded; send positive response
      ...
  }
  // prepare to send response to client
  FD_SET(fd, &wr);
  FD_CLR(fd, &rd);
  break;
}
```



Read Event (4)

```
case TRANSFER:
  // should be in midst of receiving file contents from client
  if (ret == 0) {
    // eof: all done
    close(c->fd);
    close(fd);
    FD_CLR(fd, &rd);
    break;
  }
  if (write(c->fd, c->buf, ret) == -1) {
    // write to file failed: terminate connection to client
    ...
    break;
  }
  // continue to read more data from client
  break;
}
```



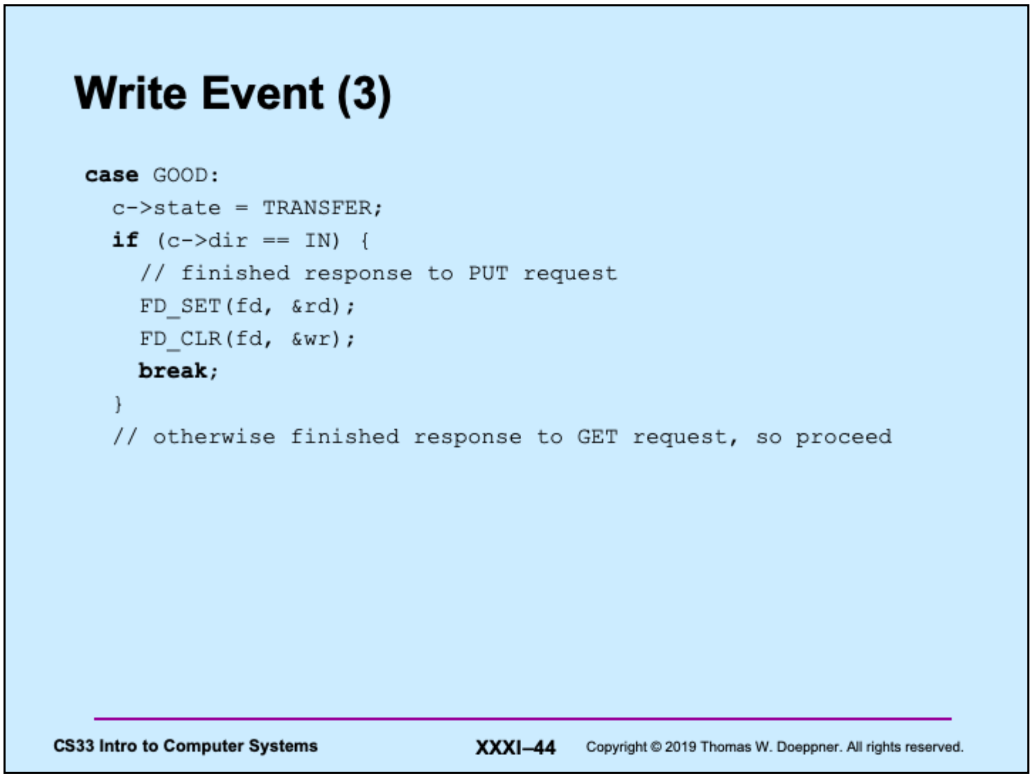
Write Event (1)

```
// File descriptor fd is ready to be written to. Write to it, then,
// depending on current state, prepare for the next action.
void write_event(int fd) {
  client_t *c = &clients[fd];
  int ret = write(fd, c->buf, c->size);
  if (ret == -1) {
    // couldn't write to client; terminate connection
    close(c->fd);
    close(fd);
    FD_CLR(fd, &wr);
    c->fd = -1;
    perror("write to client");
    return;
  }
  switch (c->state) {
```

As with handling a read event, when the server has a write event, it uses the file descriptor to determine which client to write to. (A write event indicates that it's now possible to write to the client.)

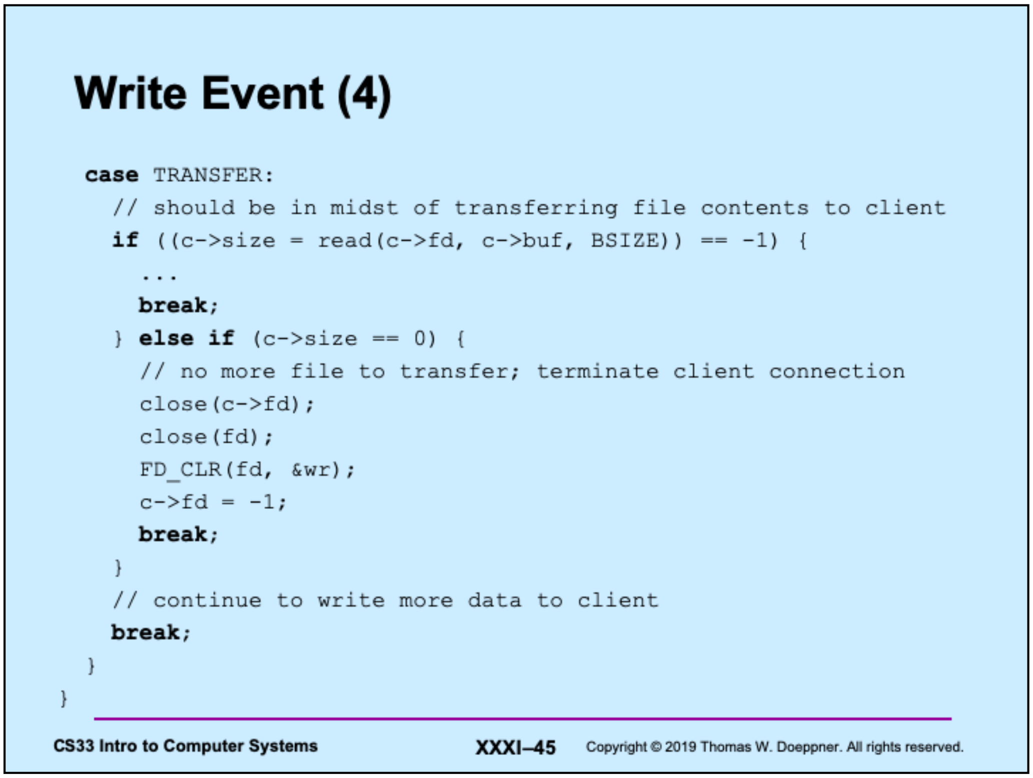
Write Event (2)

```
case BAD:
  // finished sending error message; now terminate client connection
  close(c->fd);
  close(fd);
  FD_CLR(fd, &wr);
  c->fd = -1;
  break;
```



Write Event (3)

```
case GOOD:
  c->state = TRANSFER;
  if (c->dir == IN) {
    // finished response to PUT request
    FD_SET(fd, &rd);
    FD_CLR(fd, &wr);
    break;
  }
  // otherwise finished response to GET request, so proceed
```



Write Event (4)

```
 case TRANSFER:
  // should be in midst of transferring file contents to client
  if ((c->size = read(c->fd, c->buf, BSIZE)) == -1) {
   ...
   break;
  } else if (c->size == 0) {
   // no more file to transfer; terminate client connection
   close(c->fd);
   close(fd);
   FD_CLR(fd, &wr);
   c->fd = -1;
   break;
  }
  // continue to write more data to client
  break;
 }
}
```

Problems

- Works fine as long as the protocol is followed correctly
  - can client (malicious or incompetent) cause server to misbehave?
- How can the server limit the number of clients?
- How does server limit file access?