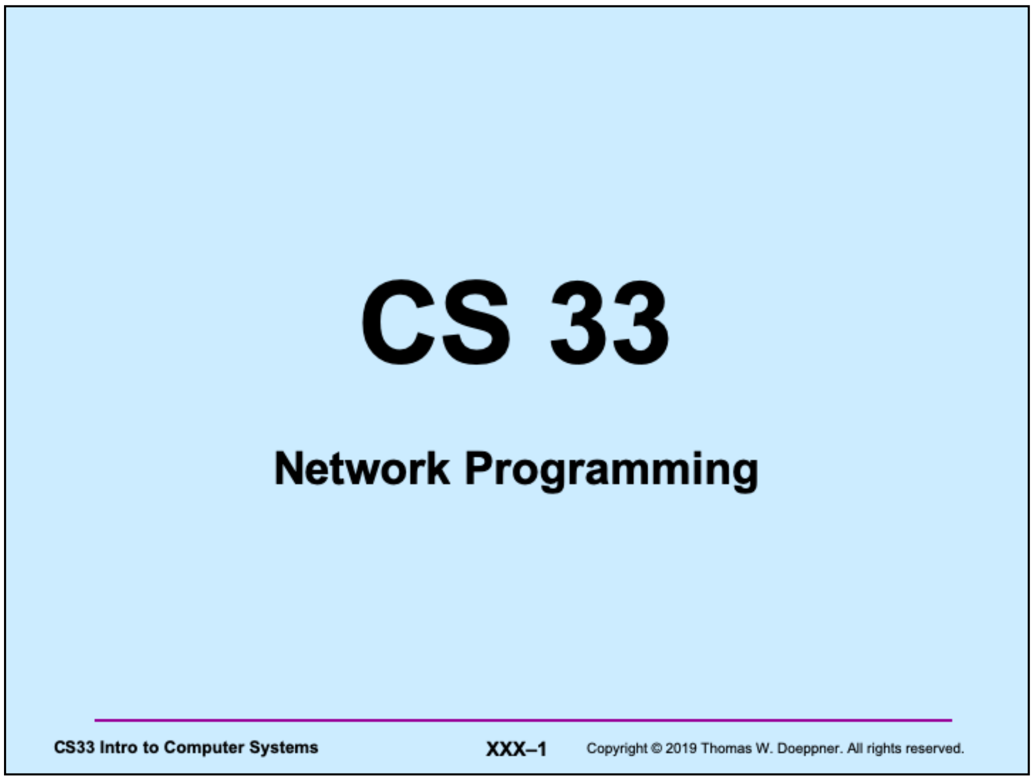
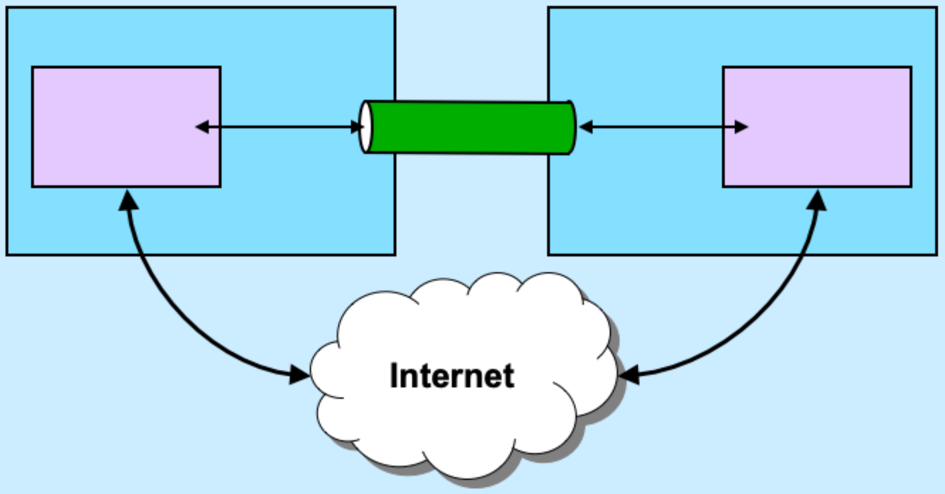


CS 33

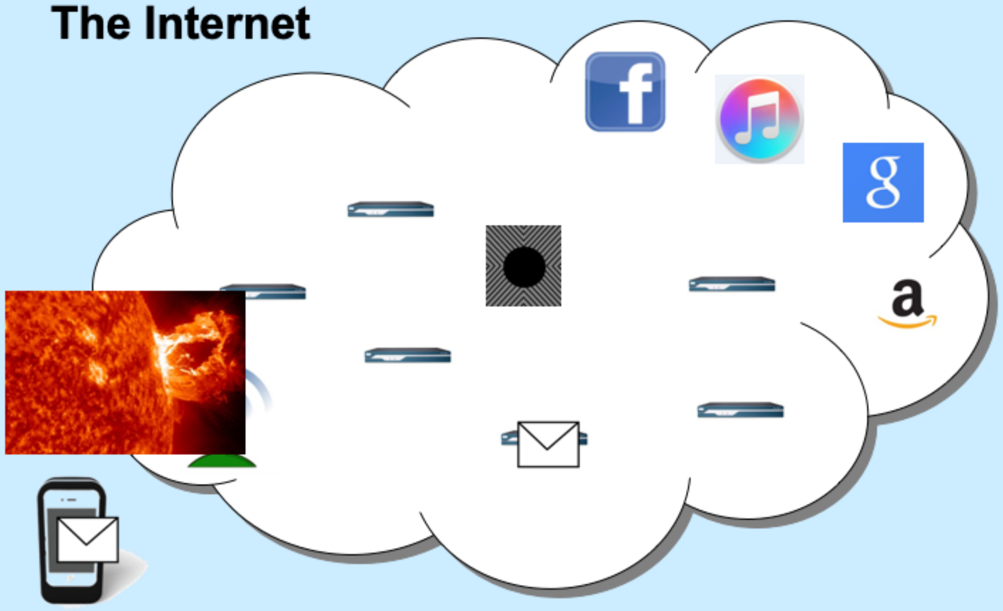
Network Programming

The source code used in this lecture, as well as some additional related source code, is on the course web page.

Communicating Over the Internet



The Internet



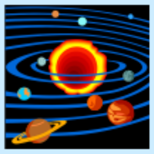
Names and Addresses

- cslab1c.cs.brown.edu
  - the name of a computer on the internet
  - mapped to an internet address
- www.nyt.com
  - the name of a service on the internet
  - mapped to a number of internet addresses

- How are names mapped to addresses?
  - domain name service (DNS): a distributed database
- How are the machines corresponding to internet addresses found?
  - with the aid of various routing protocols

Internet Addresses

- IP (internet protocol) address
  - one per network interface
  - 32 bits (IPv4)
    - » 5527 per acre of RI
    - » 25 per acre of Texas
  - 128 bits (IPv6)
    - » 1.6 billion per cubic mile of a sphere whose radius is the mean distance from the Sun to the (former) planet Pluto
- Port number
  - one per application instance per machine
  - 16 bits
    - » port numbers less than 1024 are reserved for privileged applications



Notation

- Addresses (assume IPv4: 32-bit addresses)
  - written using dot notation
    - 128.48.37.1
      - dots separate bytes
  - address plus port (1426):
    - 128.48.37.1:1426

Reliability

- Two possibilities
  - don't worry about it
    - » just send it
      - if it arrives at its destination, that's good!
        - no verification
  - worry about it
    - » keep track of what's been successfully communicated
      - receiver "acks"
    - » retransmit until
      - data is received

      or
      - it appears that "the network is down"

Reliability vs. Unreliability

- Reliable communication
  - good for
    - » email
    - » texting
    - » distributed file systems
    - » web pages
  - bad for
    - » streaming audio
    - » streaming video

$\left.\begin{array}{l}\text{streaming audio}\\\text{streaming video}\end{array}\right\}$ a little noise is better than a long pause

The Data Abstraction

- Byte stream
  - sequence of bytes
    - » as in pipes
  - any notion of a larger data aggregate is the responsibility of the programmer
- Discrete records
  - sequence of variable-size “records”
  - boundaries between records maintained
  - receiver receives discrete records, as sent by sender

What's Supported

- Stream
  - byte-stream data abstraction
  - reliable transmission
- Datagram
  - discrete-record data abstraction
  - unreliable transmission

Quiz 1

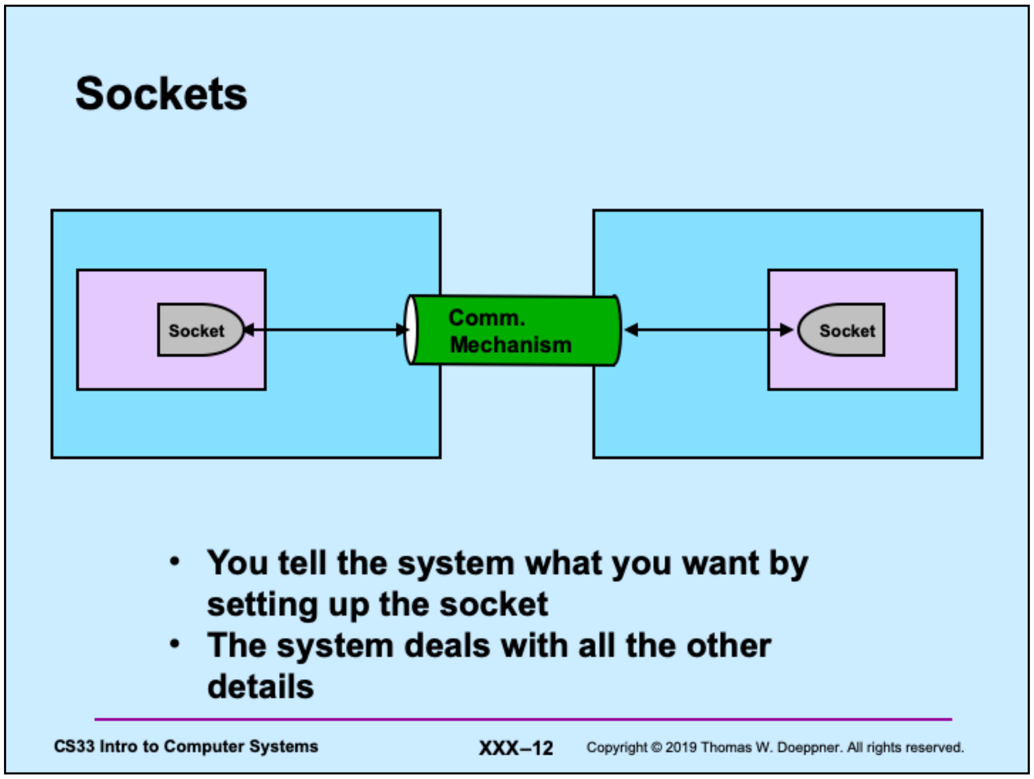
The following code is used to transmit data over a reliable byte-stream communication channel. Assume sizeof(data) is large.

```
// sender
record_t data=getData();
write(fd, &data,
  sizeof(data));
```

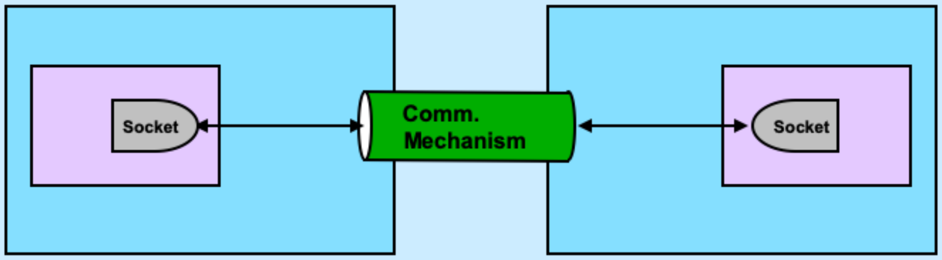
```
// receiver
read(fd, &data,
  sizeof(data));
useData(data);
```

Does it work?

- a) always
- b) always, assuming no network problems
- c) sometimes
- d) never

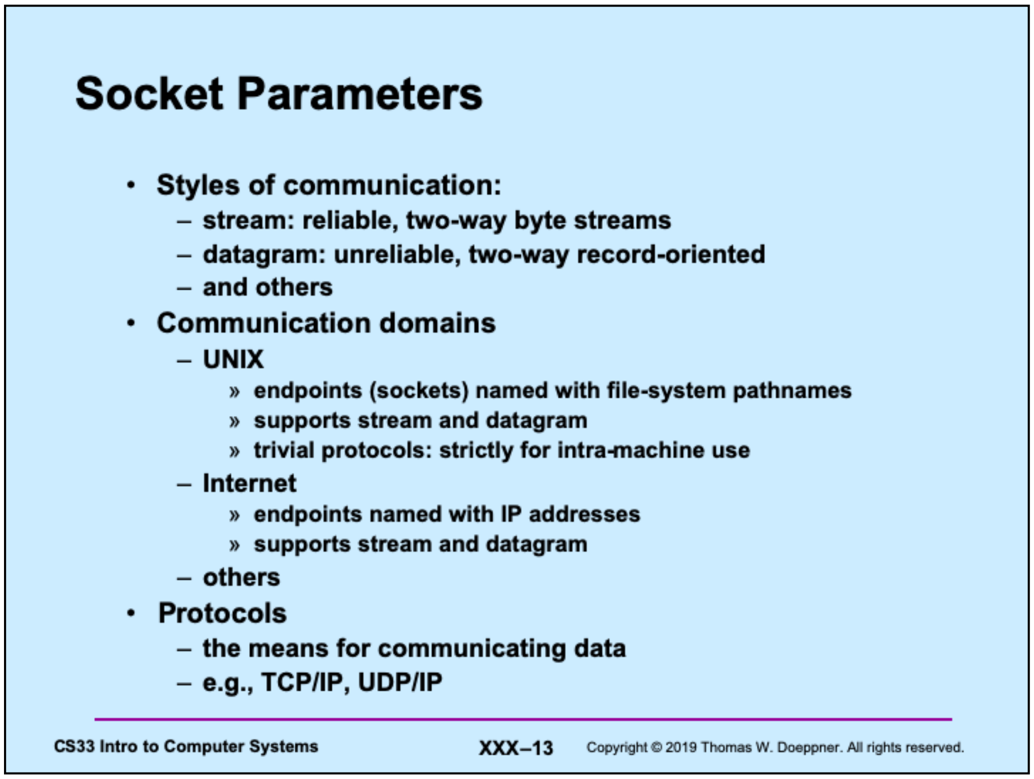


Sockets



- You tell the system what you want by setting up the socket
- The system deals with all the other details

Sockets are the abstraction of the communication path. An application sets up a socket as the basis for communication. It refers to it via a file descriptor.



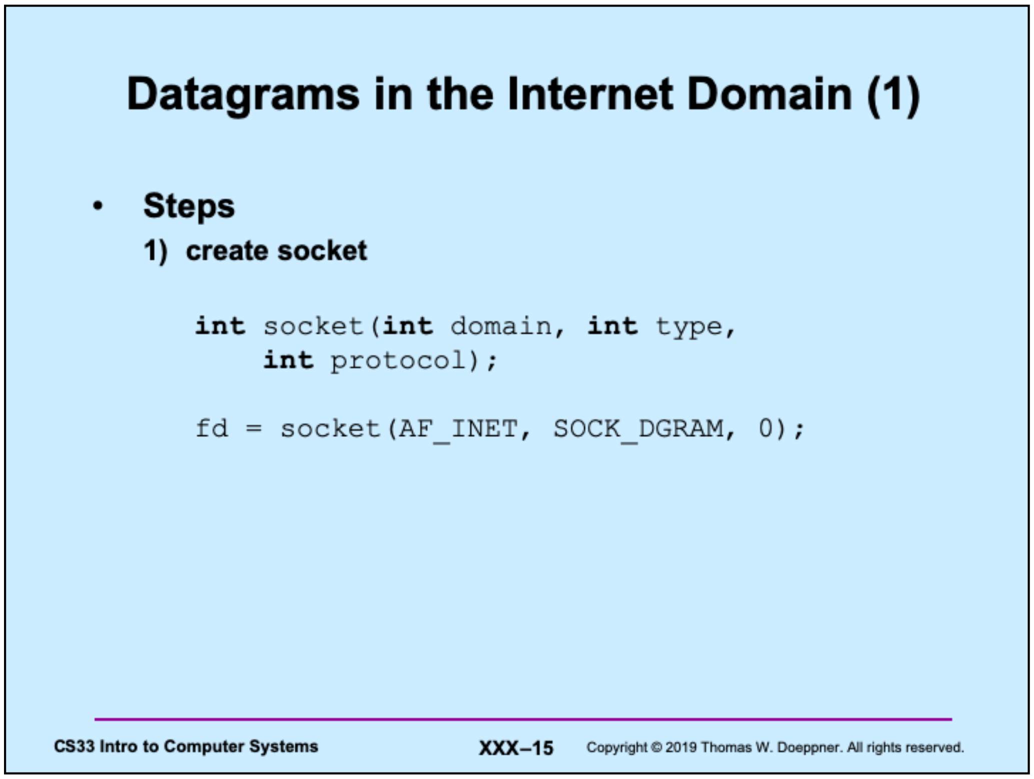
Socket Parameters

- Styles of communication:
  - stream: reliable, two-way byte streams
  - datagram: unreliable, two-way record-oriented
  - and others
- Communication domains
  - UNIX
    - » endpoints (sockets) named with file-system pathnames
    - » supports stream and datagram
    - » trivial protocols: strictly for intra-machine use
  - Internet
    - » endpoints named with IP addresses
    - » supports stream and datagram
  - others
- Protocols
  - the means for communicating data
  - e.g., TCP/IP, UDP/IP

We focus strictly on the internet domain.

Setting Things Up

- Socket (communication endpoint) is given a name
  - *bind* system call
- Datagram communication
  - use *sendto* system call to send data to named recipient
  - use *recvfrom* system call to receive data and name of sender
- Stream communication
  - client connects to server
    - » server uses *listen* and *accept* system calls to receive connections
    - » client uses *connect* system call to make connections
  - data transmitted using *send* or *write* system calls
  - data received using *recv* or *read* system calls

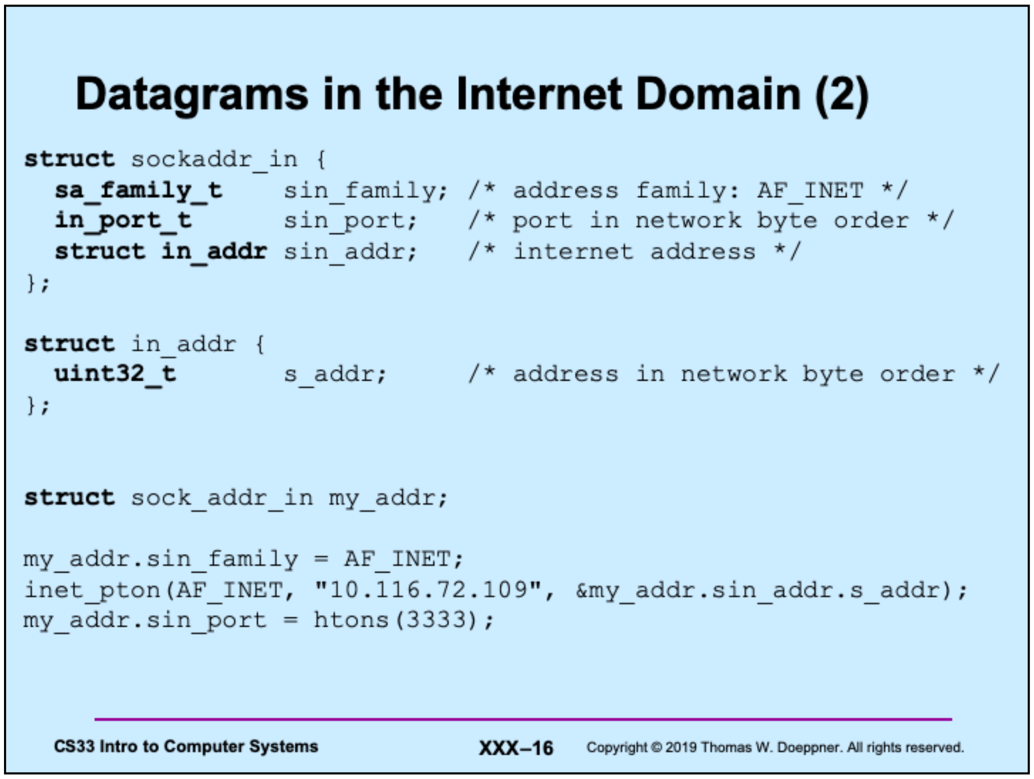


Datagrams in the Internet Domain (1)

- **Steps**
  1) **create socket**

```
int socket(int domain, int type,
    int protocol);

fd = socket(AF_INET, SOCK_DGRAM, 0);
```

The first step is to create a socket. We request a datagram socket in the Unix domain. The third argument specifies the protocol, but since in this and pretty much all examples the protocol is determined by the first two arguments, a zero may be used. For datagrams in the internet domain, the protocol is UDP (user datagram protocol).



Datagrams in the Internet Domain (2)

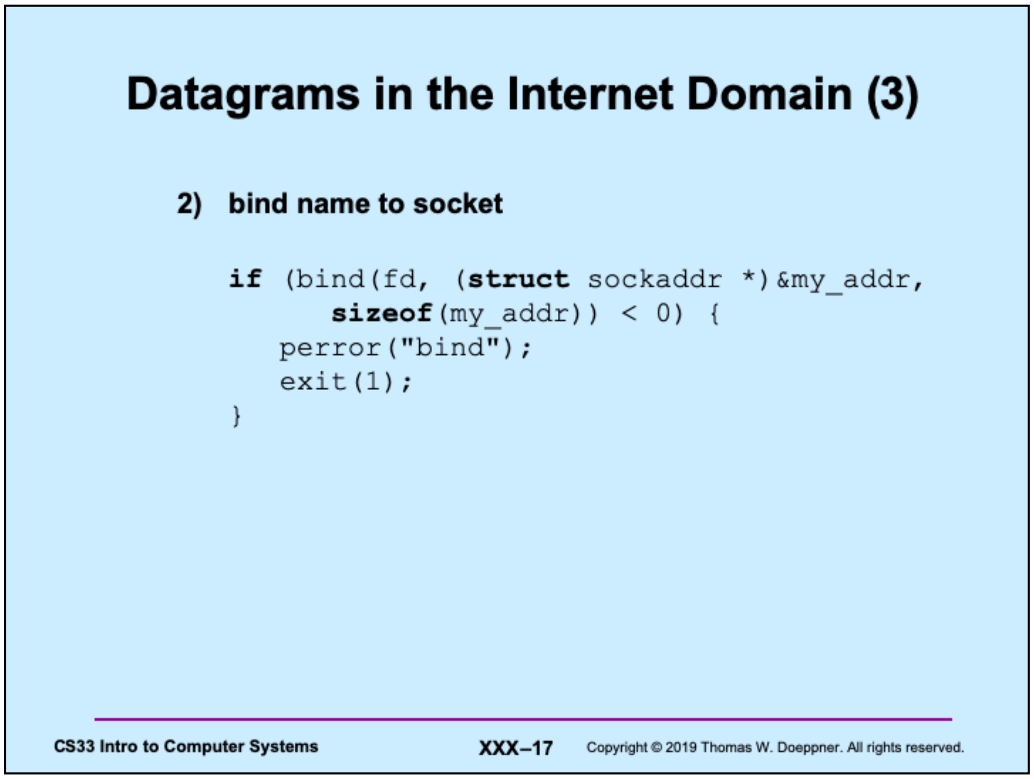
```
struct sockaddr_in {
  sa_family_t    sin_family; /* address family: AF_INET */
  in_port_t      sin_port;   /* port in network byte order */
  struct in_addr sin_addr;   /* internet address */
};

struct in_addr {
  uint32_t       s_addr;     /* address in network byte order */
};


struct sock_addr_in my_addr;

my_addr.sin_family = AF_INET;
inet_pton(AF_INET, "10.116.72.109", &my_addr.sin_addr.s_addr);
my_addr.sin_port = htons(3333);
```

Setting the network address is surprisingly complicated.

One issue is the datatype of the address. Here we use struct sockaddr_in, which is used for addresses in the internet domain (which is the only kind of address we'll be using). Many functions that use network addresses as arguments expect them to be of type "struct sockaddr". struct sockaddr_in is, essentially, a struct sock_addr specialized for the internet domain. If C were an object-oriented language, a sockaddr_in would be a subclass of sockaddr. As it is, we'll need to use casts to get functions expecting a pointer to a sockaddr to accept a pointer to a sockaddr_in.

Another issue has to do with the byte order of integers on the local computer. Since different computers might have different byte orders, this could be a problem. One byte order is chosen as the standard; for network use, all must convert to that order if necessary. The macros “htonl()” (“host to network long”) and “htons()” (“host to network short”) do the conversions if necessary. Note that the port number is converted to a short int in network byte order. Network byte order is defined to be big-endian (and thus conversion is required on IA-32 and x86-64 machines).

The other issue is translating an internet address in dot notation into a 32-bit integer (or 128-bit integer for IPv6) in network byte order. This is accomplished with the library routine inet_pton (Printable form to Network byte order). Its first argument is either AF_INET (for IPv4) or AF_INET6 (for IPv6). Its second argument is the string to be converted, and its third argument is a pointer to where the result should go.

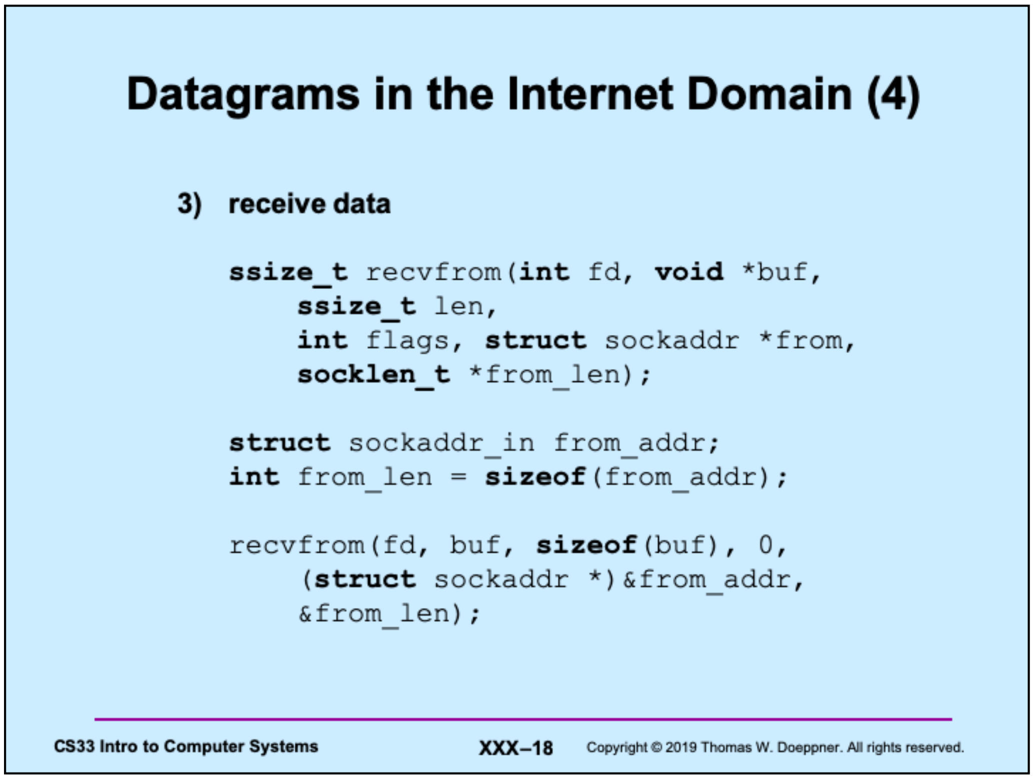


Datagrams in the Internet Domain (3)

2) bind name to socket

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

The bind system call is used to pass the name to the kernel and use it to name the socket. Bind takes a generic *struct sockaddr ** argument; since we have a struct sockaddr_in *, we have to use a cast. Since the size of the address depends on the domain, the size is suppled as the third argument.

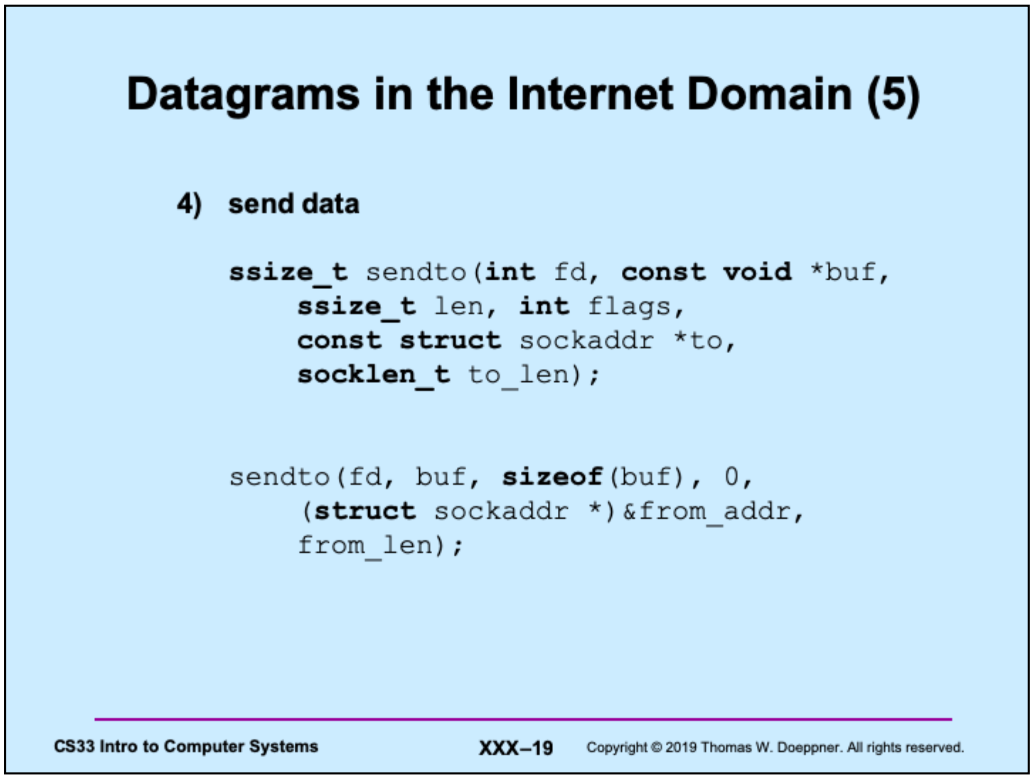


Datagrams in the Internet Domain (4)

3) **receive data**

```
ssize_t recvfrom(int fd, void *buf,
    ssize_t len,
    int flags, struct sockaddr *from,
    socklen_t *from_len);

struct sockaddr_in from_addr;
int from_len = sizeof(from_addr);

recvfrom(fd, buf, sizeof(buf), 0,
    (struct sockaddr *)&from_addr,
    &from_len);
```

Use the *recvfrom* system call not only to receive data, but also to obtain the sender's address. The *from_len* parameter is both an input and an output parameter. On input, it gives the size of the area of memory pointed to by *from*. On output, it gives the size of the portion of that memory that was actually used.



Datagrams in the Internet Domain (5)

4) send data

```
ssize_t sendto(int fd, const void *buf,
    ssize_t len, int flags,
    const struct sockaddr *to,
    socklen_t to_len);


sendto(fd, buf, sizeof(buf), 0,
    (struct sockaddr *)&from_addr,
    from_len);
```

Use the *sendto* system call to send data to a particular destination socket. In this case, we're sending a response to whoever sent the previous message.

Quiz 2

Suppose a process on one machine sends a datagram to a process on another machine. The sender uses *sendto* and the receiver uses *recvfrom*. There's a momentary problem with the network and the datagram doesn't make it to the receiving process. Its call to *recvfrom*

a) doesn't return

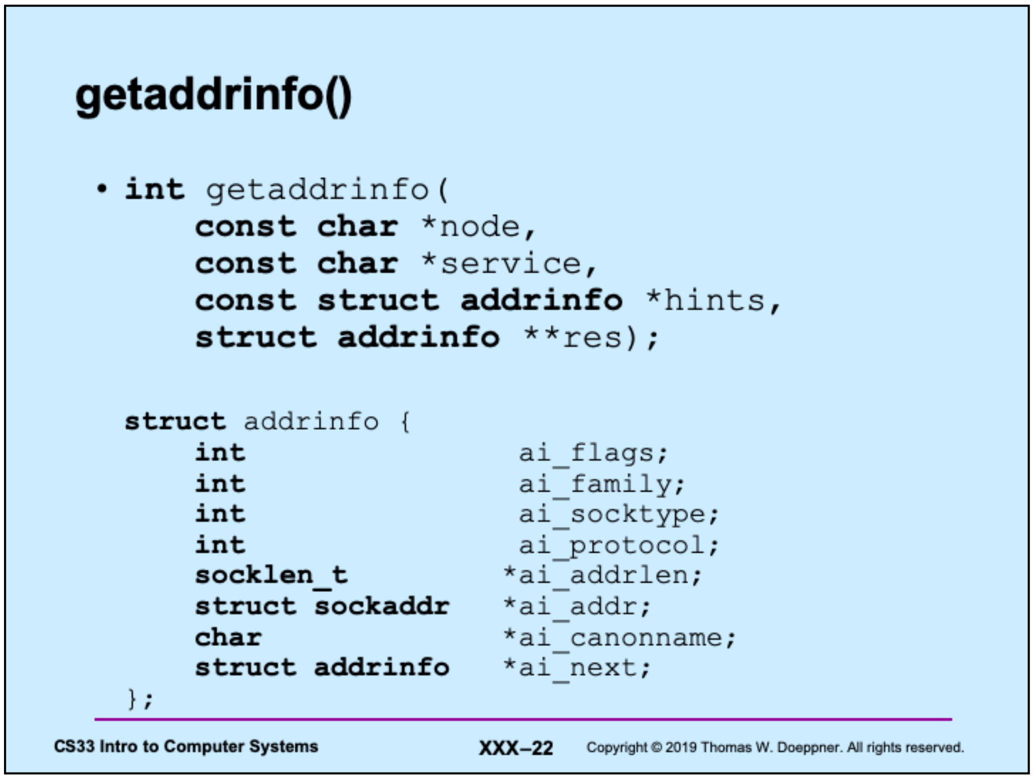
b) returns –1 (indicating an error)

c) returns 0

d) returns some other value

Using DNS

- Translate names to addresses using *getaddrinfo*
  - looks up name in DNS, gets list of possible addresses

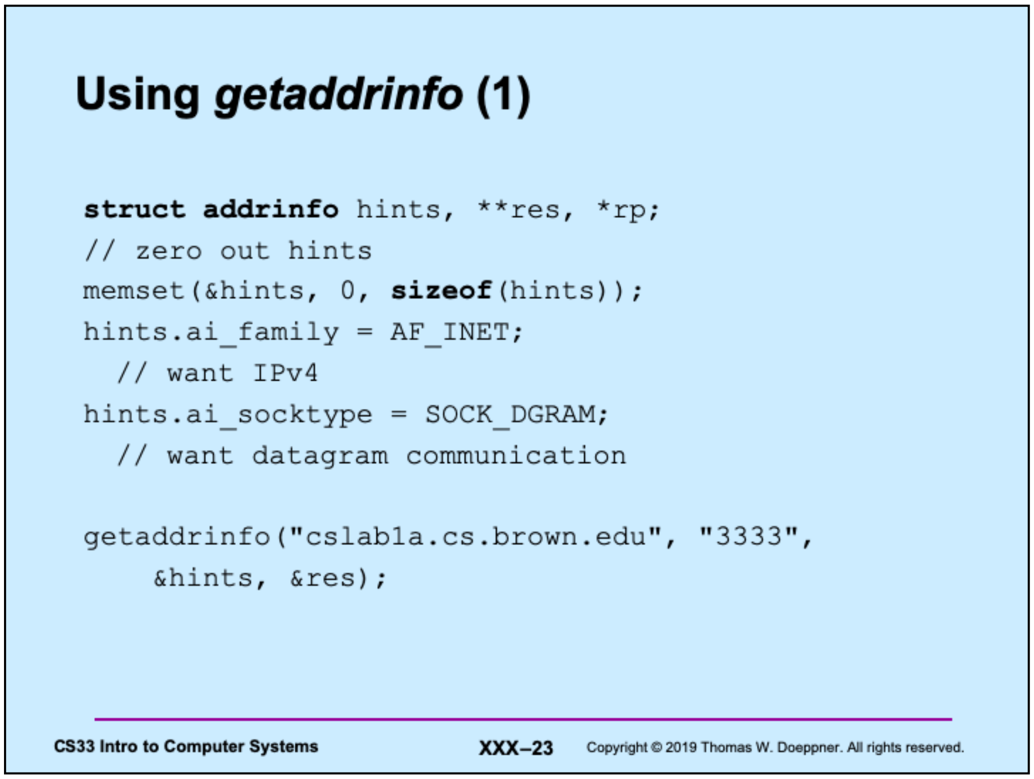


getaddrinfo()

-
  ```
  int getaddrinfo(
      const char *node,
      const char *service,
      const struct addrinfo *hints,
      struct addrinfo **res);
  ```

```
struct addrinfo {
    int                  ai_flags;
    int                  ai_family;
    int                  ai_socktype;
    int                  ai_protocol;
    socklen_t           *ai_addrlen;
    struct sockaddr     *ai_addr;
    char                *ai_canonname;
    struct addrinfo     *ai_next;
};
```

The general idea of using *getaddrinfo* is that you supply the name of the host you'd like to contact (*node*), which service on that host (*service*), and a description of how you'd like to communicate (*hints*). It returns a list of possible means for contacting the server in the form of a list of addrinfo structures (*res*).

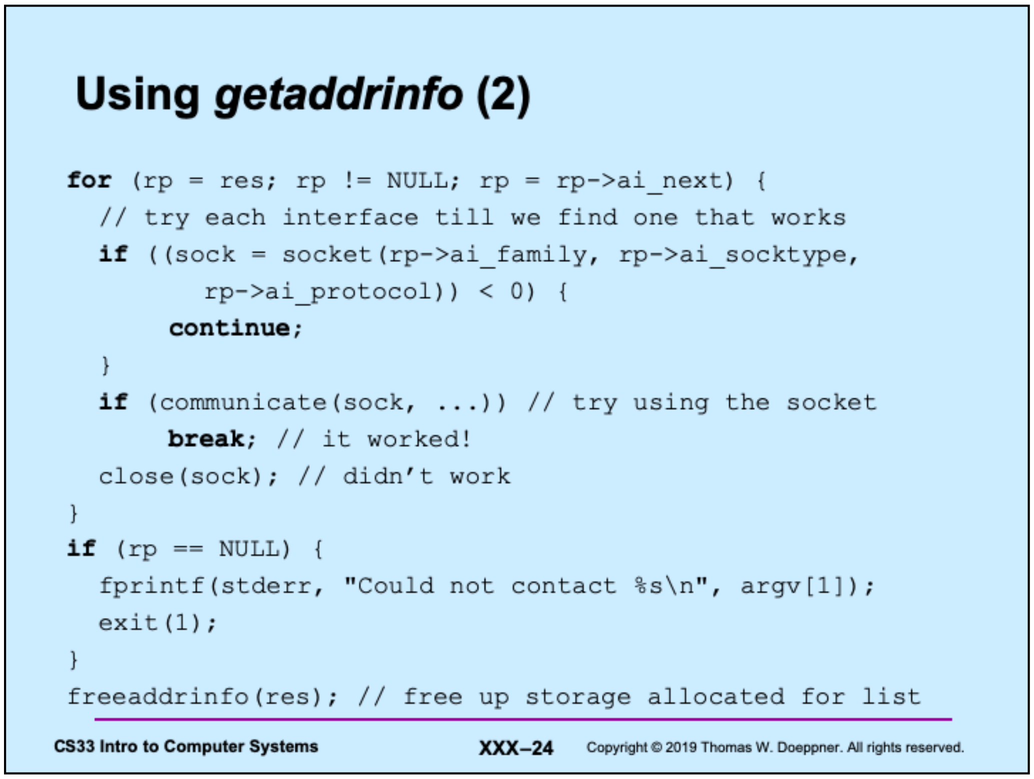


Using *getaddrinfo* (1)

```
struct addrinfo hints, **res, *rp;
// zero out hints
memset(&hints, 0, sizeof(hints));
hints.ai_family = AF_INET;
  // want IPv4
hints.ai_socktype = SOCK_DGRAM;
  // want datagram communication

getaddrinfo("cslab1a.cs.brown.edu", "3333",
    &hints, &res);
```

The general idea of using *getaddrinfo* is that you supply the name of the host you'd like to contact (*node*), which service on that host (*service*), and a description of how you'd like to communicate (*hints*). It returns a list of possible means for contacting the server in the form of a list of addrinfo structures (*res*). Here we've specified the service as a port number (in ASCII). It could also be specified as a standard service name — such names are listed in the file /etc/services.

Note that much of the hints structure is not specified. Thus we first initialize the whole thing to zeroes, then fill in the part we want to specify.

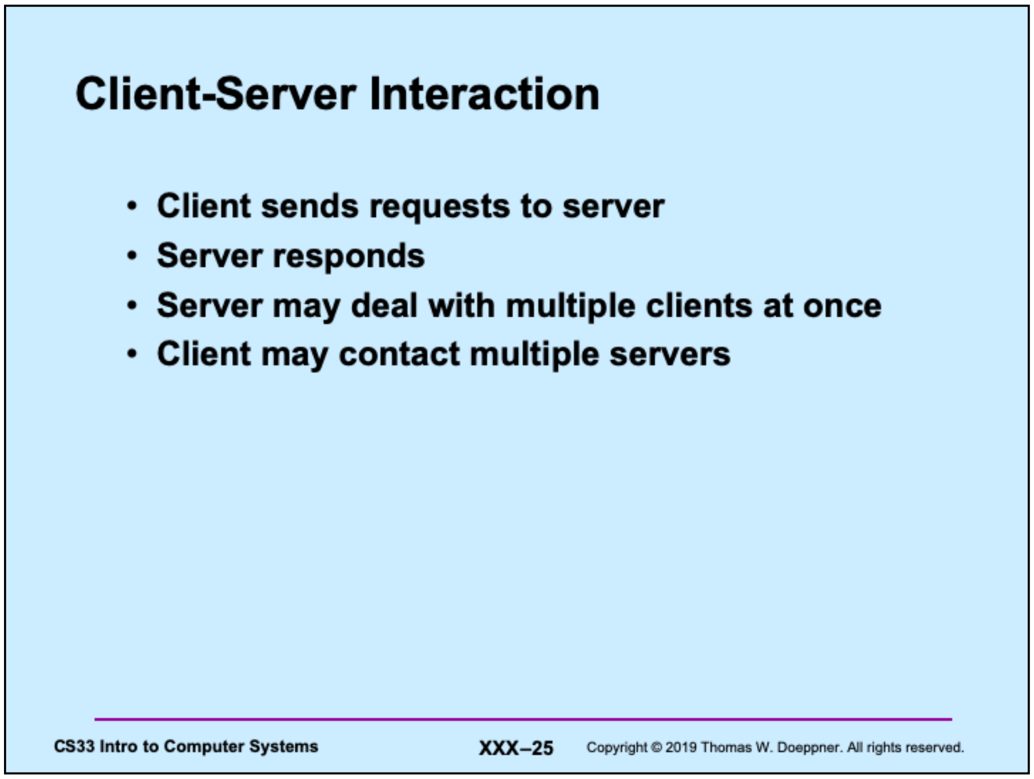


Using *getaddrinfo* (2)

```
for (rp = res; 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 (communicate(sock, ...)) // try using the socket
      break; // it worked!
  close(sock); // didn't work
}
if (rp == NULL) {
  fprintf(stderr, "Could not contact %s\n", argv[1]);
  exit(1);
}
freeaddrinfo(res); // free up storage allocated for list
```

getaddrinfo returns, via its *res* output argument, a list of interfaces. We try each in turn until we find one that works.

Note that the list was *malloc*'d within *getaddrinfo* and must be freed by calling *freeaddrinfo*.

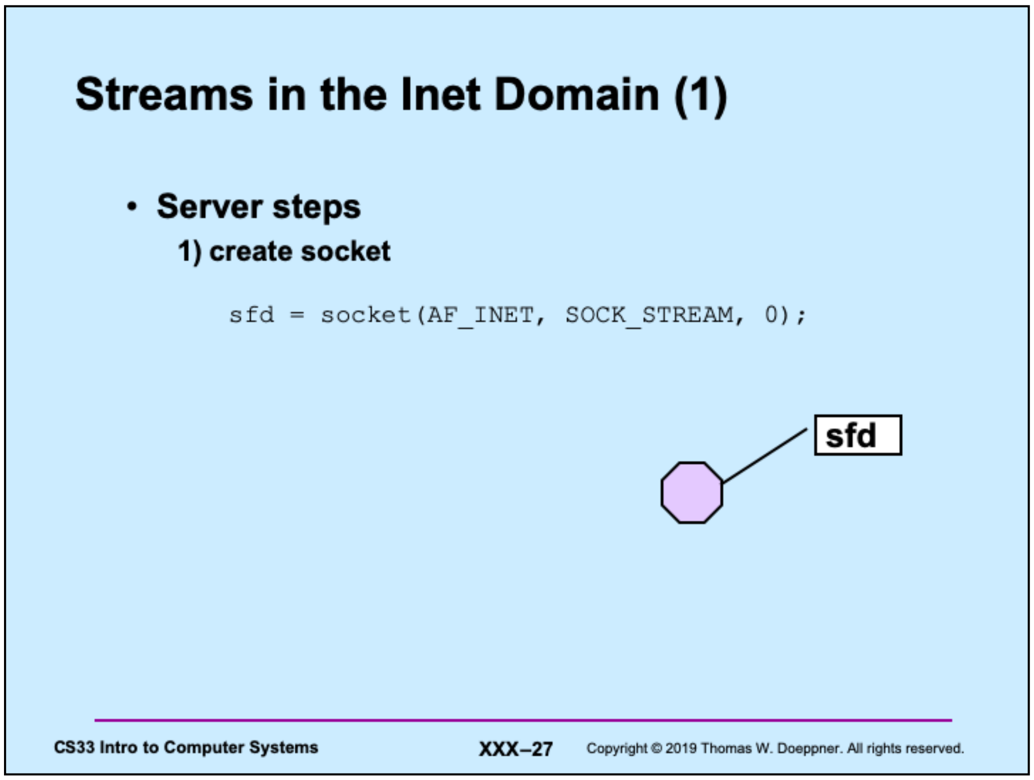


Client-Server Interaction

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

Reliable Communication

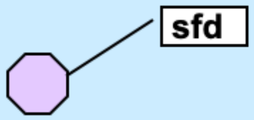
- The promise …
  - what is sent is received
  - order is preserved
- Set-up is required
  - two parties agree to communicate
  - within the implementation of the protocol:
    - » each side keeps track of what is sent, what is received
    - » received data is acknowledged
    - » unack'd data is re-sent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



Streams in the Inet Domain (1)

- **Server steps**
  1) create socket

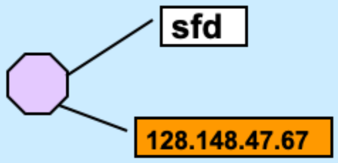
```
sfd = socket(AF_INET, SOCK_STREAM, 0);
```

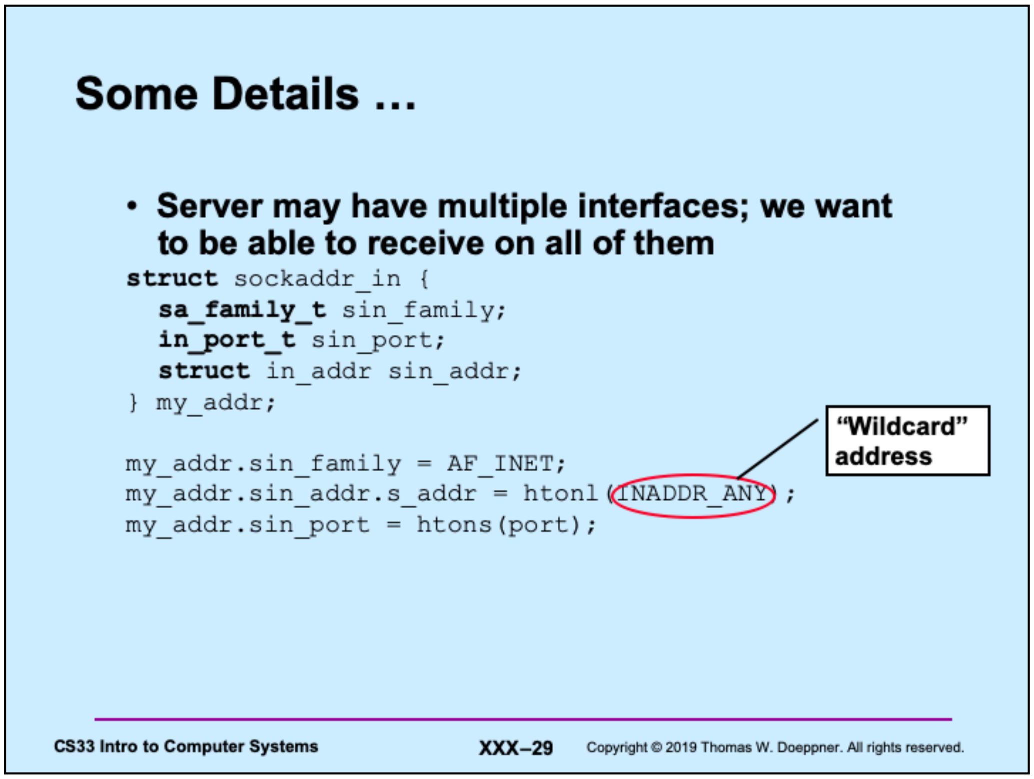


Streams in the Inet Domain (2)

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

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





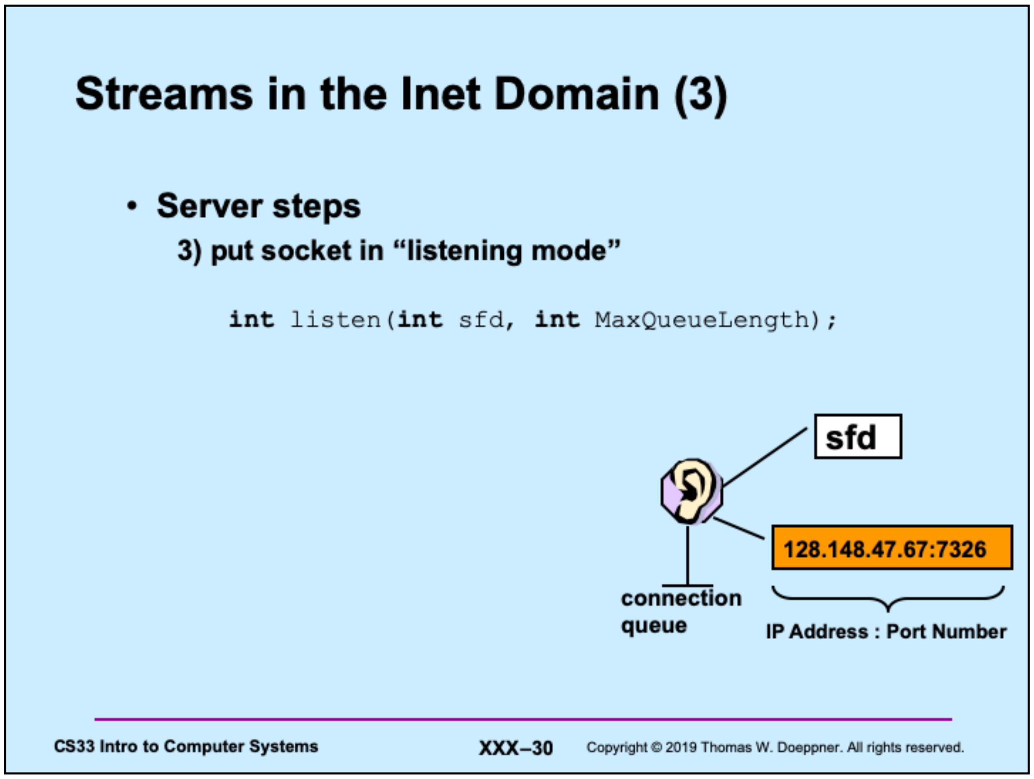
Some Details …

- **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

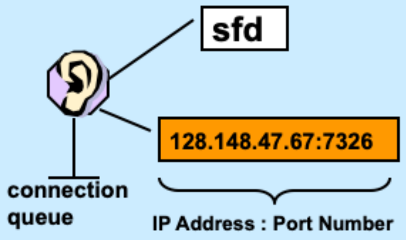
A machine might have multiple addresses — this is often the case for servers. Rather than having to specify all of them, one simply gives the "wildcard" address, meaning all the addresses on the machine. This is useful even on a machine with just one network interface, since the wildcard address in that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

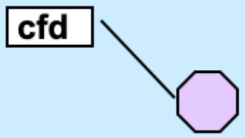


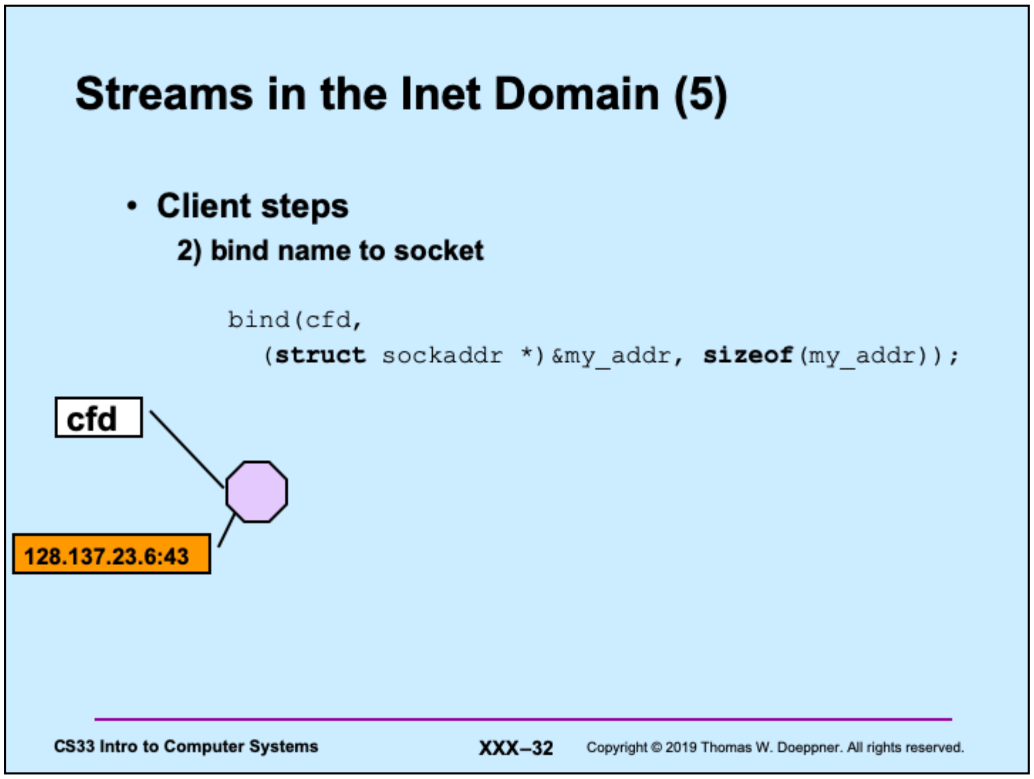
The *listen* system call tells the OS that the process would like to receive connections from clients via the indicated socket. The MaxQueueLength argument is the maximum number of connections that may be queued up, waiting to be accepted. Its maximum value is in /proc/sys/net/core/somaxconn (and is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

Streams in the Inet Domain (4)

- **Cient steps**
  - **1) create socket**

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

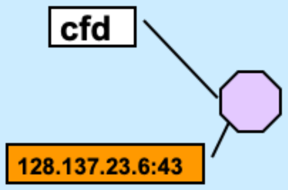


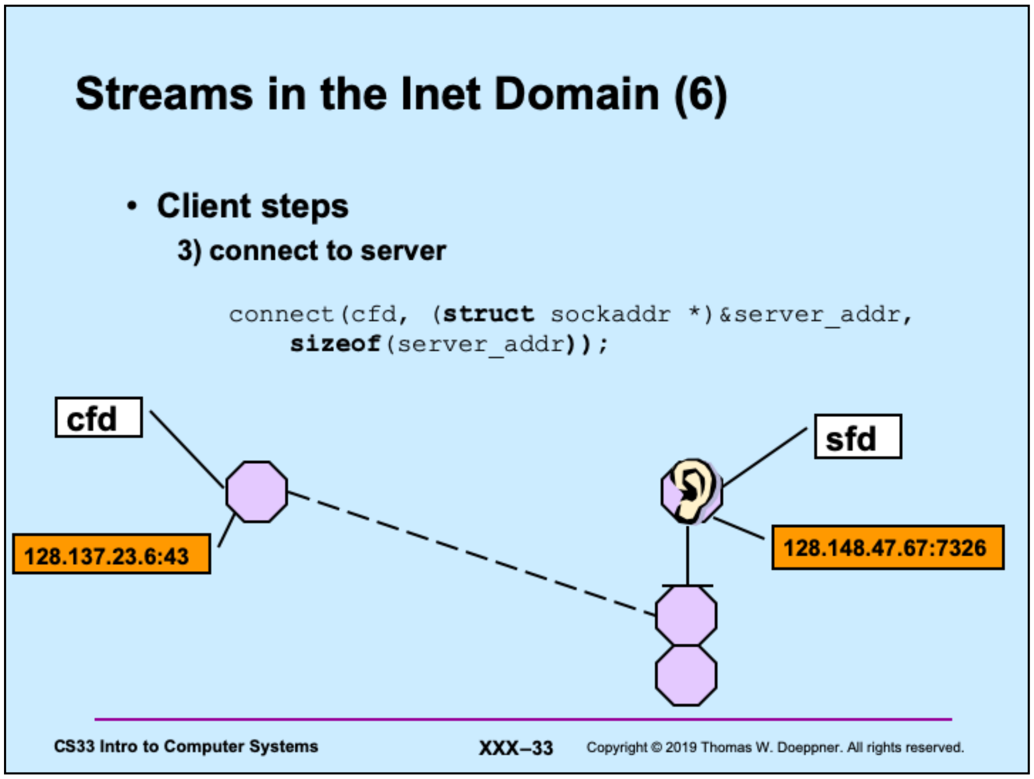


Streams in the Inet Domain (5)

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

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

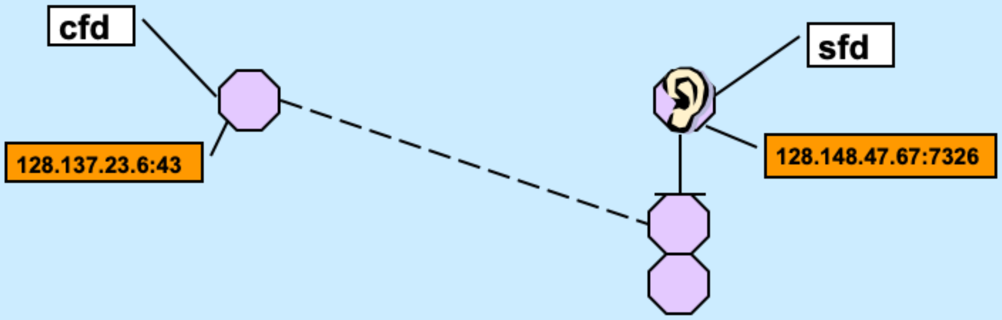




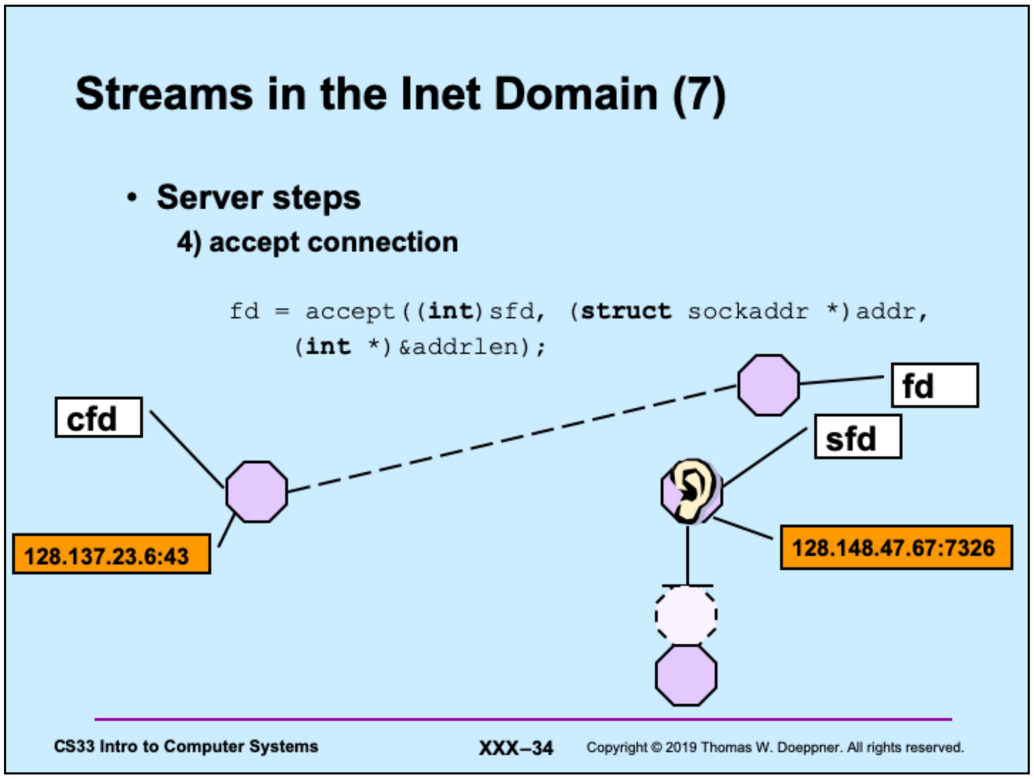
Streams in the Inet Domain (6)

- **Client steps**
  - **3) connect to server**

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



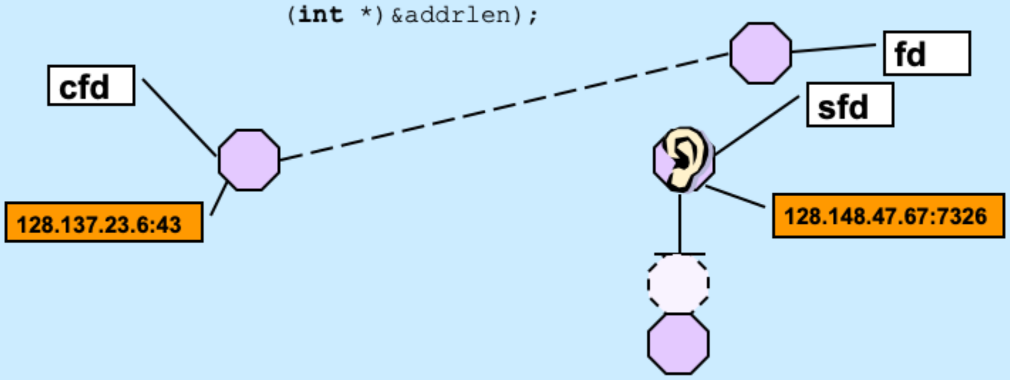
The client issues the *connect* system call to initiate a connection with the server. The first argument is a file descriptor referring to the client's socket. Ultimately this socket will be connected to a socket on the server. Behind the scenes the client OS communicates with the server OS via a protocol-specific 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).



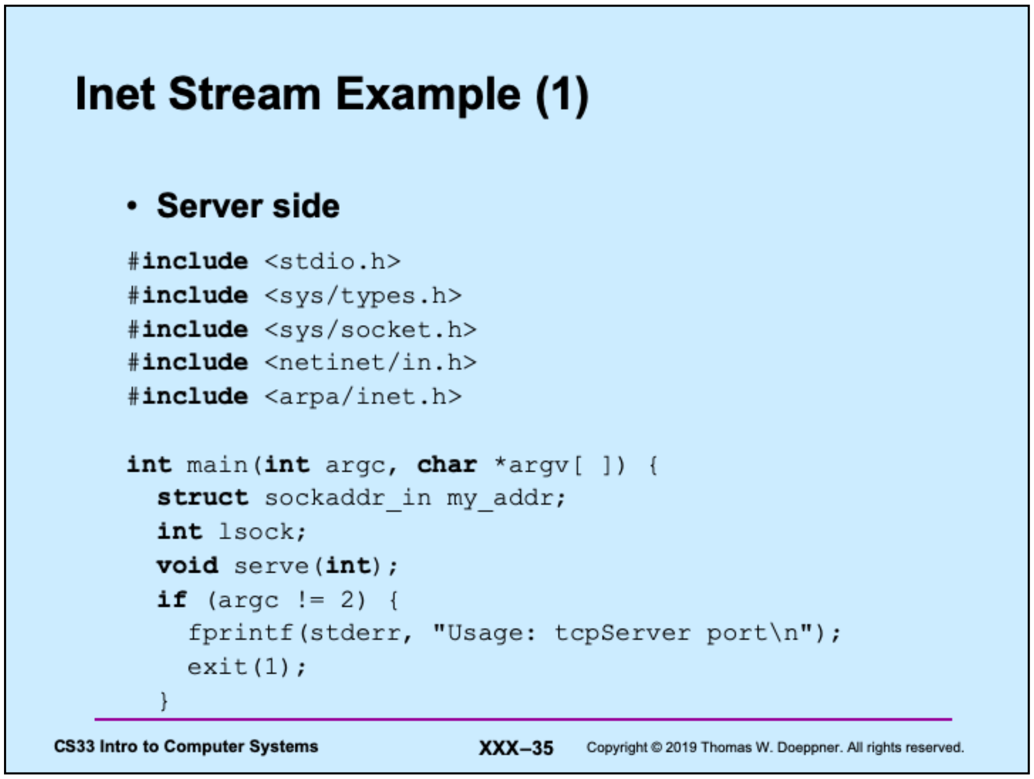
Streams in the Inet Domain (7)

- **Server steps**
  4) 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)

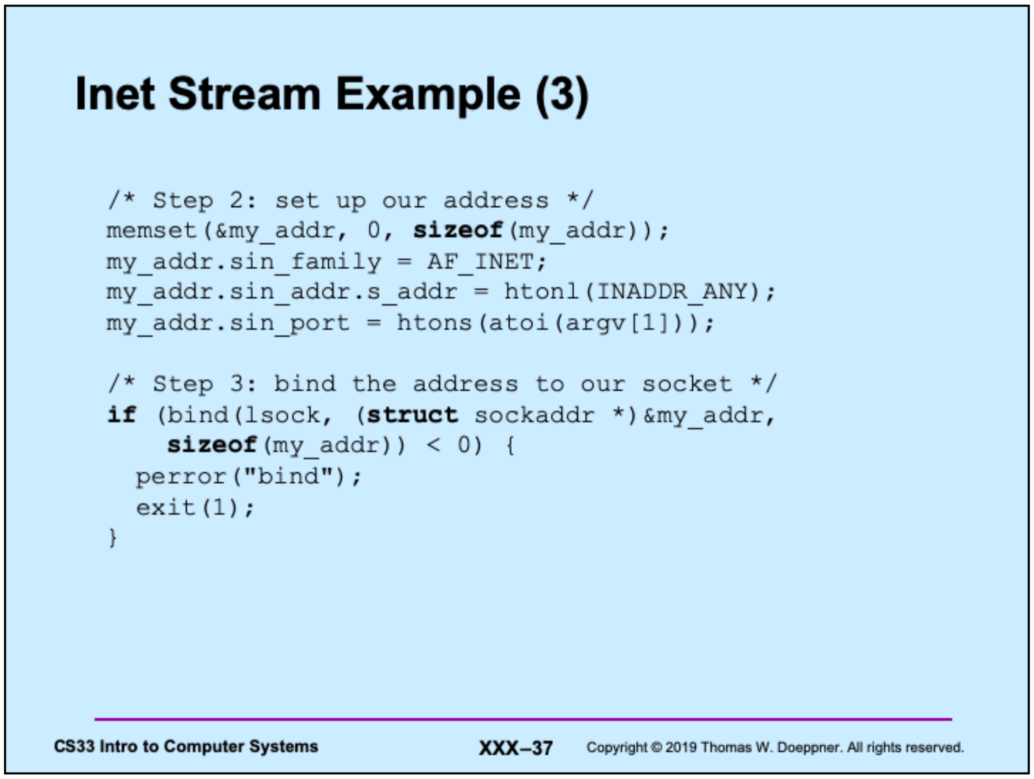
- **Server side**

```
#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.

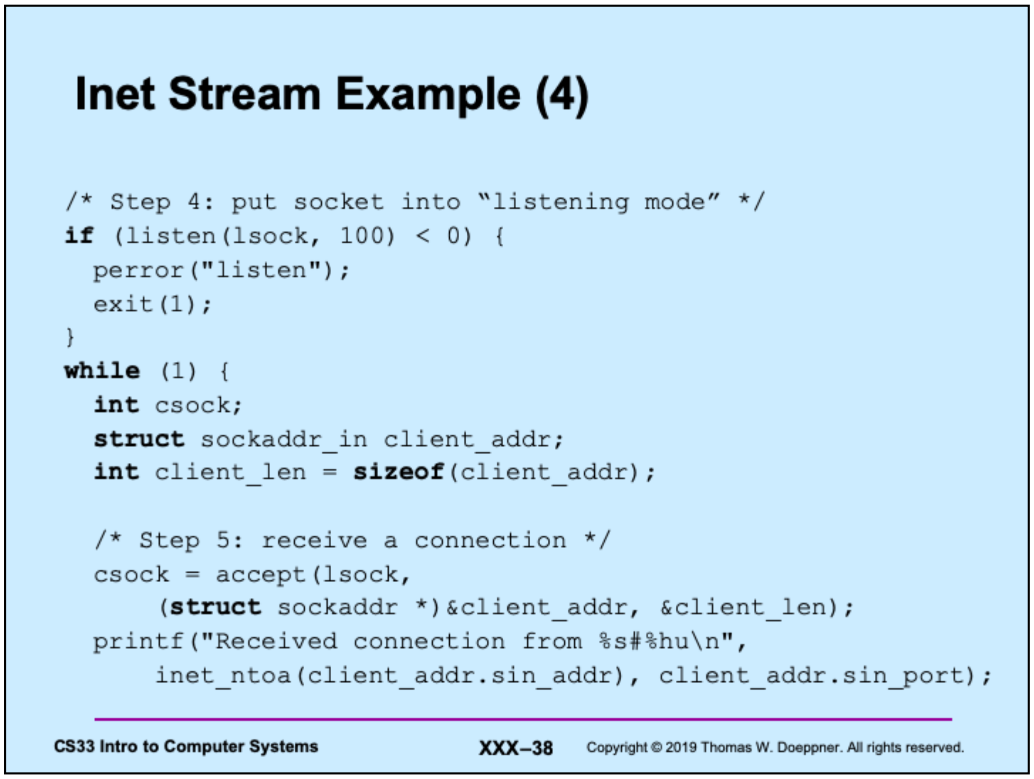
Inet Stream Example (2)

```
// 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);
}
```

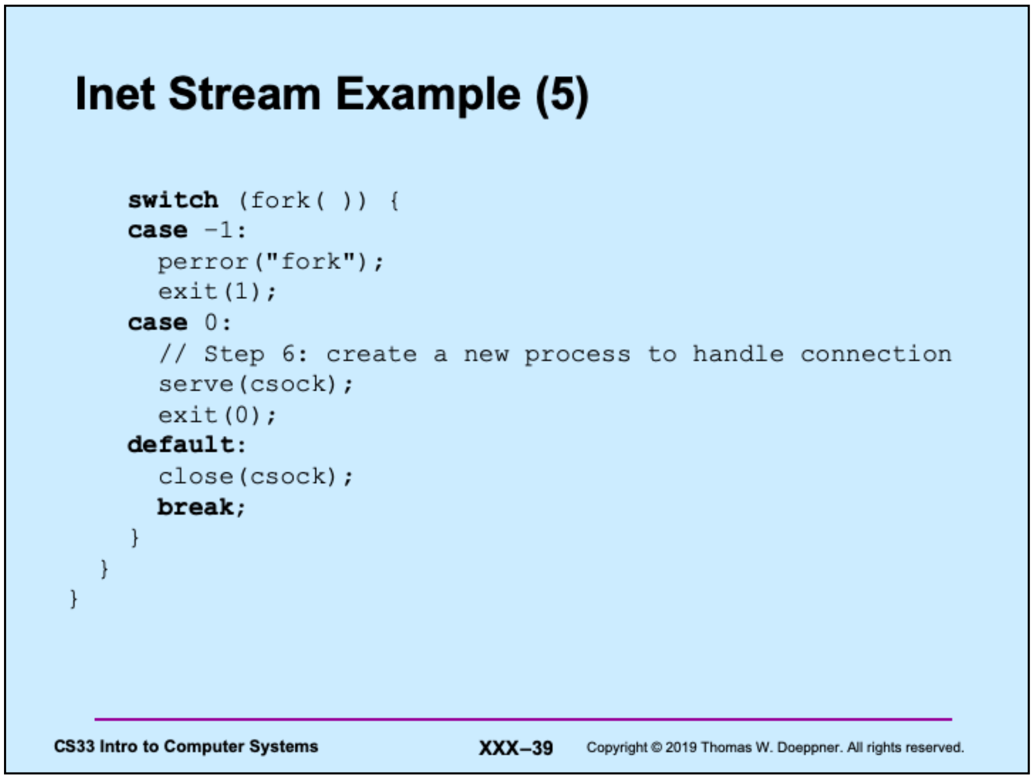
The *memset* command copies some number of instances of its second argument into what its first argument points to. The number of instances is given by its third argument. As used here it is setting *my_addr* to all zeroes.



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.

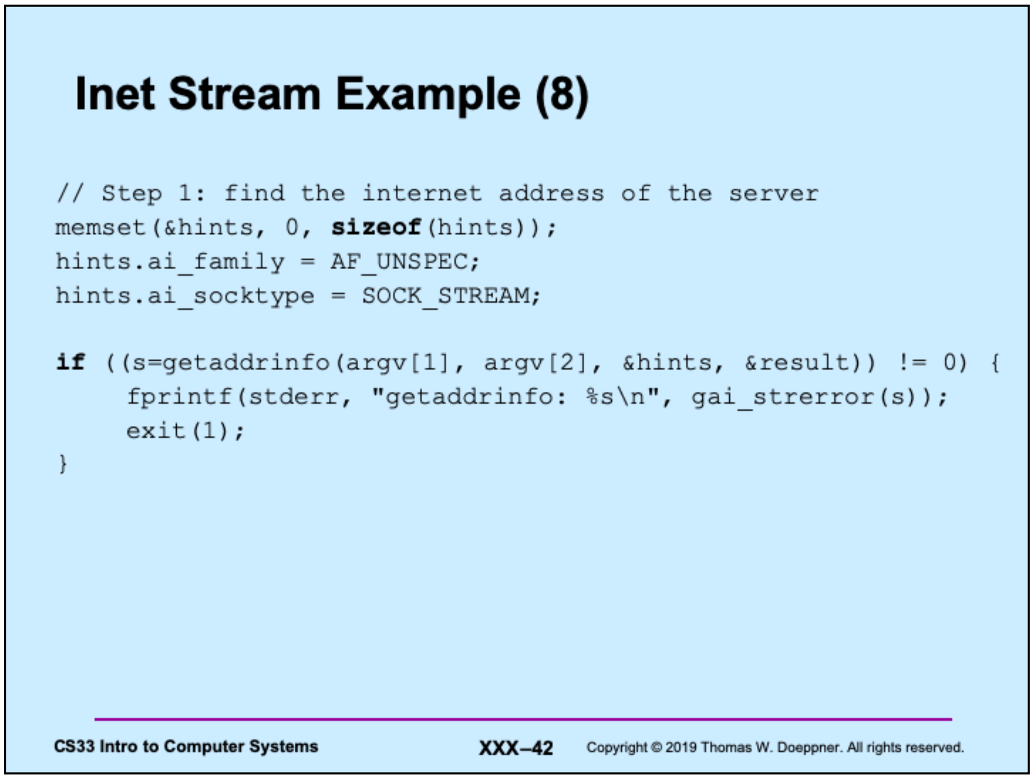
Inet Stream Example (6)

```
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);
}
```

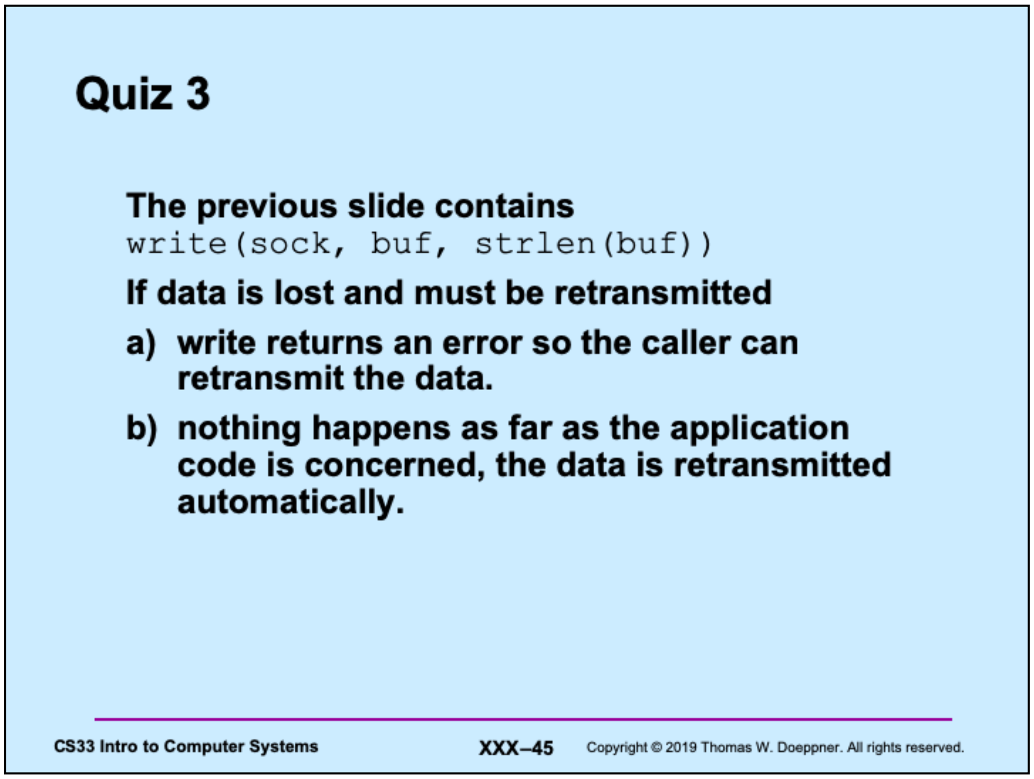
We specify AF_UNSPEC for the address family, which allows us to connect to hosts supporting either IPv4 or IPv6.

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 3

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 4

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.