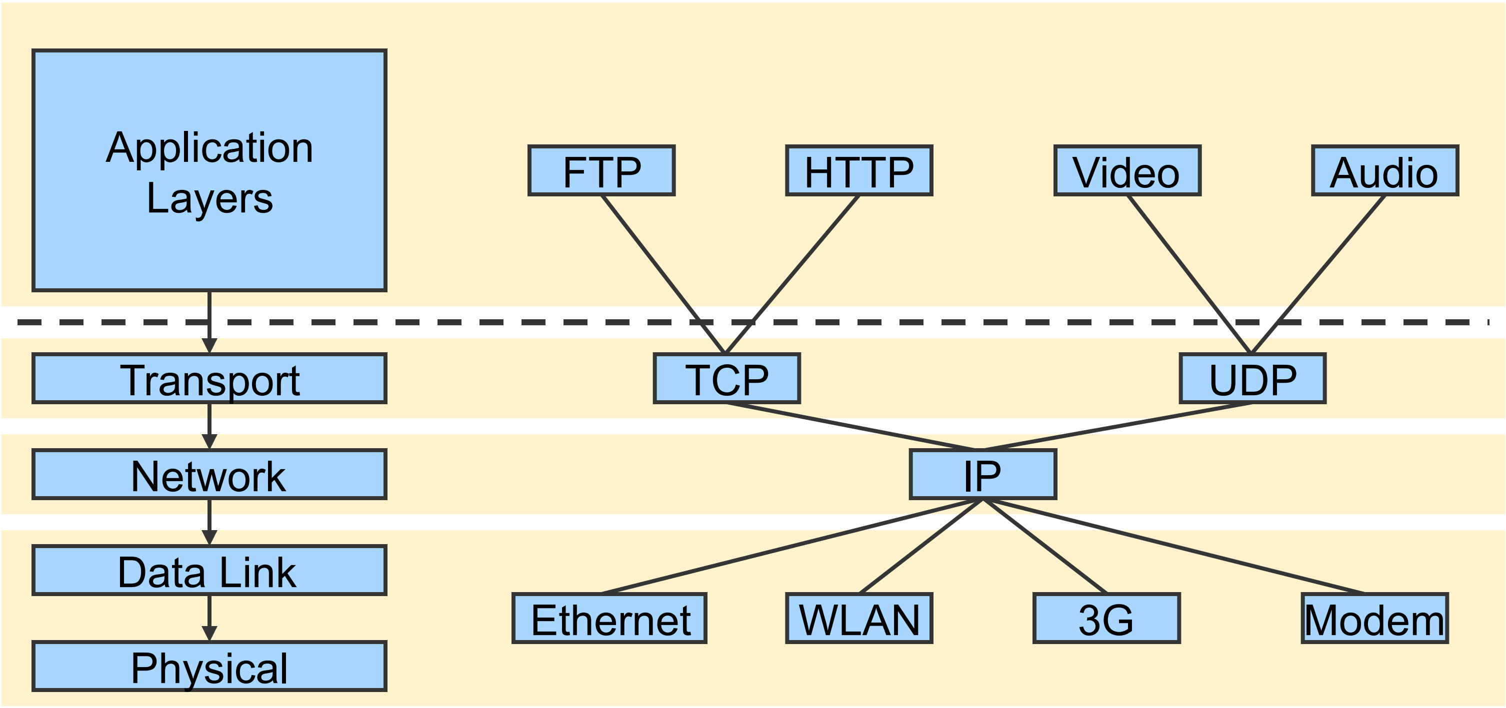
Lecture 2: Introduction to Unix Network Programming

Reference: Stevens Unix Network Programming

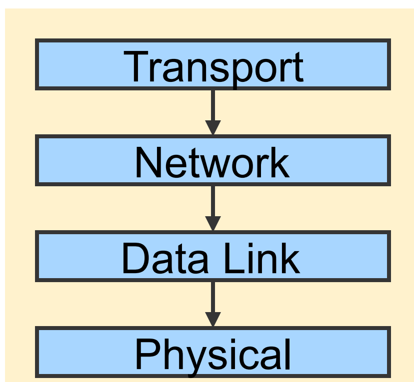
Internet Protocols



Programming and Principles

Programming

learn to use Internet for communication (with focus on implementation of networking concepts)



learn to build network from ground up

Principles and Concepts

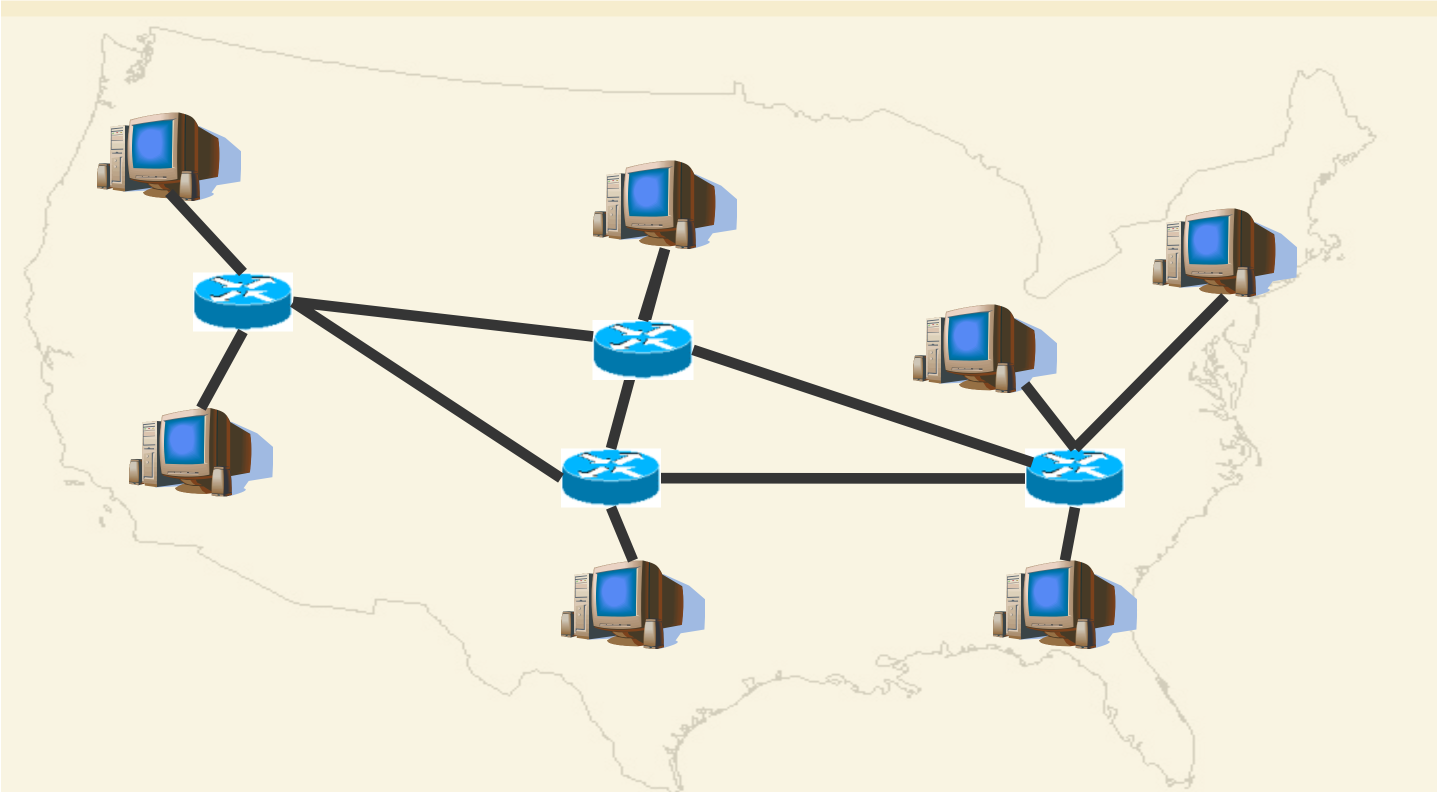
Network Programming

- How should two hosts communicate with each other over the Internet?
  - The "Internet Protocol" (IP)
  - Transport protocols: TCP, UDP
- How should programmers interact with the protocols?
  - Sockets API – application programming interface

Network Programming with Sockets

- Sockets API
  - An interface to the transport layer
    - Introduced in 1981 by BSD 4.1
    - Implemented as library and/or system calls
    - Similar interfaces to TCP and UDP
    - Can also serve as interface to IP (for super-user); known as "raw sockets"

How can many hosts communicate?

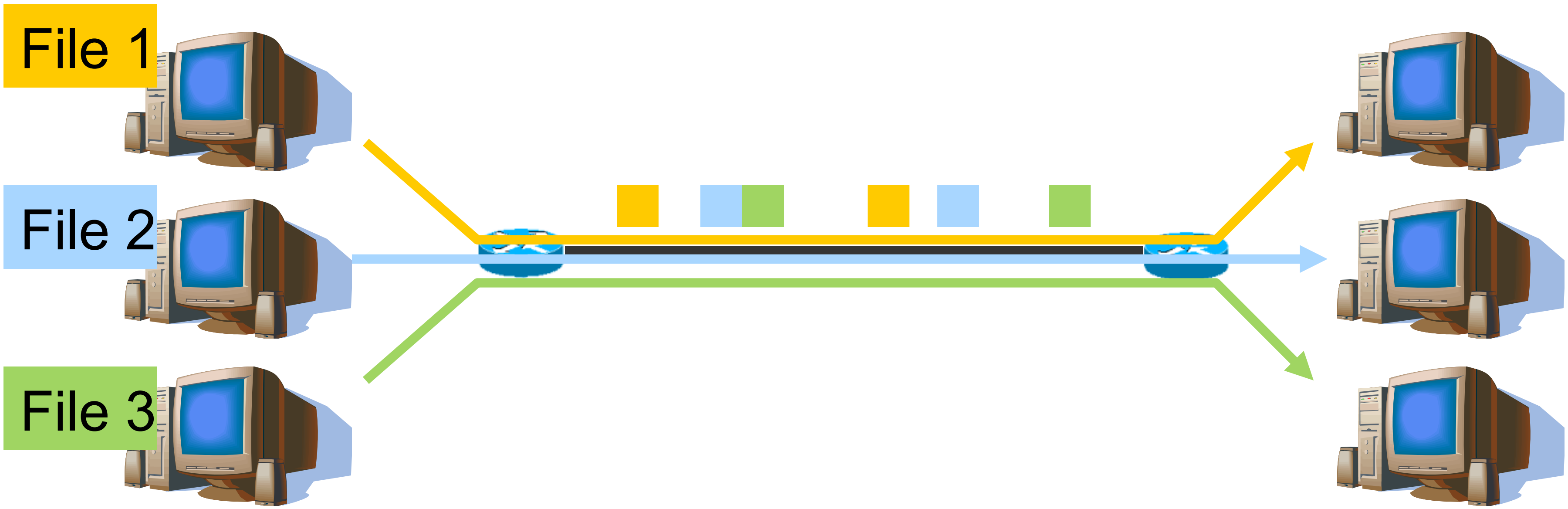


- Multiplex traffic with routers
- Question: How to identify the destination?
- Question: How to share bandwidth across different flows?

Identifying hosts with Addresses and Names

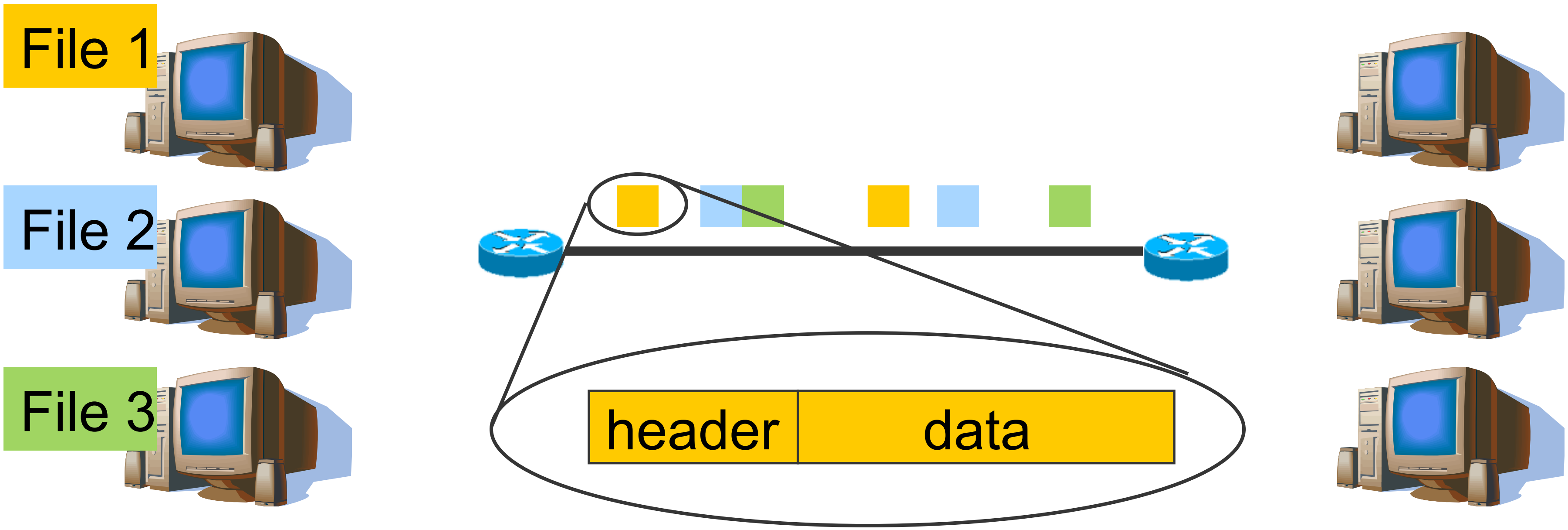
- IP addresses
  - Easily handled by routers/computers
  - Fixed length
  - E.g.: `128.121.146.100`
- But how do you know the IP address?
  - Internet domain names
  - Human readable, variable length
  - E.g.: `twitter.com`
- But how do you get the IP address from the domain name?
  - Domain Name System (DNS) maps between them

How can many hosts share network resources?



- Solution: divide traffic into “IP packets”
  - At each router, the entire packet is received, stored, and then forwarded to the next router

How can many hosts share network resources?



- Solution: divide traffic into "IP packets"
  - Use packet "headers" to denote which connection the packet belongs to
    - Contains src/dst address/port, length, checksum, time-to-live, protocol, flags, type-of-service, etc

Is IP enough?

- What if host runs multiple applications?
  - Use UDP: 16-bit “Port numbers” in header distinguishes traffic from different applications
- Or if content gets corrupted?
  - Use UDP: “Checksum” covering data, UDP header, and IP header detects flipped bits
- User Datagram Protocol (UDP)
  - Properties
    - Unreliable - no guaranteed delivery
    - Unordered - no guarantee of maintained order of delivery
    - Unlimited Transmission - no flow control
  - Unit of Transfer is “datagram” (a variable length packet)

Is UDP enough?

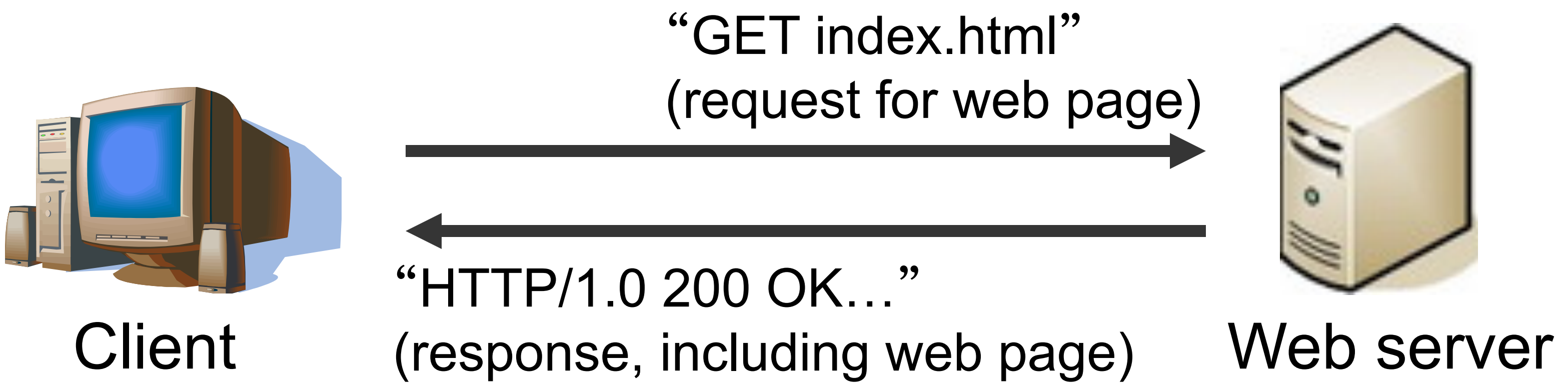
- What if network gets congested? Or packets get lost/reordered/duplicated?
- UseTransport Control Protocol (TCP)
  - Guarantees reliability, ordering, and integrity
  - Backs off when there is congestion
  - Connection-oriented (Set up connection before communicating, Tear down connection when done)
  - Gives ‘byte-stream” abstraction to application
  - Also has ports, but different namespace from UDP
- Which one is better, TCP or UDP?
- Why not other hybrid design points?

How should we program networked apps?

- How can we compose together programs running on different machines?
  - Client-server model
- What sort of interfaces should we reveal to the programmer?
  - Sockets API

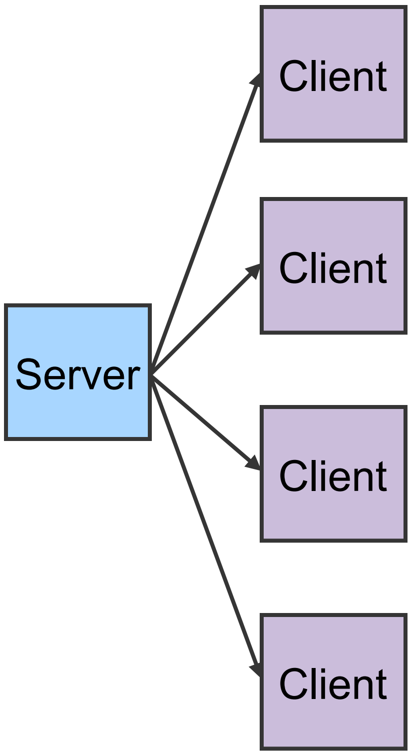
Client-Server Model

- A client initiates a request to a well-known server
- Example: the web



- Other examples: FTP, SSH/Telnet, SMTP (email), Print servers, File servers

Client-Server Model



- Asymmetric Communication
  - Client sends requests
  - Server sends replies
- Server/Daemon
  - Well-known name and port
  - Waits for contact
  - Processes requests, sends replies
- Client
  - Initiates contact
  - Waits for response

Server-side service models

- Concurrent
  - Server processes multiple clients' requests simultaneously
- Sequential
  - Server processes only one client's requests at a time
- Hybrid
  - Server maintains multiple connections, but processes responses sequentially

Wanna See Real Clients and Servers?

- Apache Web server
  - Open source server first released in 1995
  - Name derives from “a patchy server” ;-)
  - Software available online **at http://www.apache.org**
- Mozilla Web browser
  - **http://www.mozilla.org/developer/**
- Sendmail
  - **http://www.sendmail.org/**
- BIND Domain Name System
  - Client resolver and DNS server
  - **http://www.isc.org/index.pl?/sw/bind/**

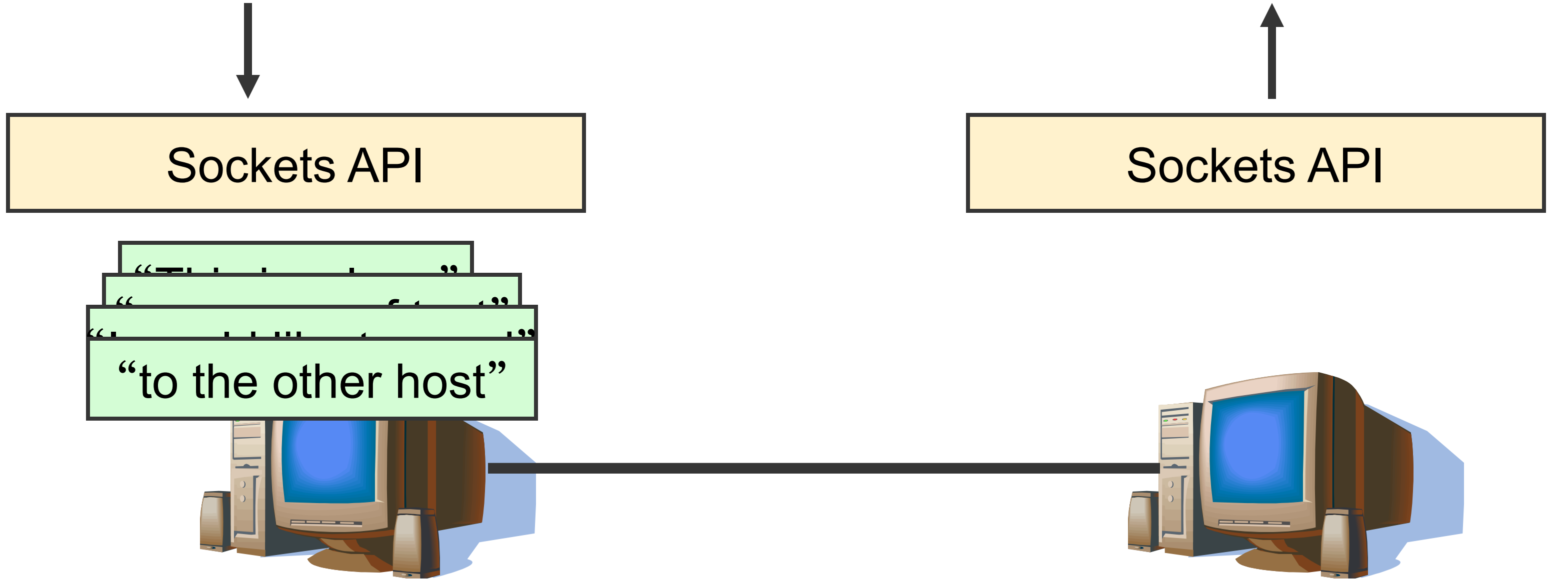
What interfaces to expose to programmer?

- Stream vs. Datagram sockets
- Stream sockets
  - Abstraction: send a long stream of characters
  - Typically implemented on top of TCP
- Datagram sockets
  - Abstraction: send a single packet
  - Typically implemented on top of UDP

Stream sockets

send(“This is a long sequence of text I would like to send to the other host”)

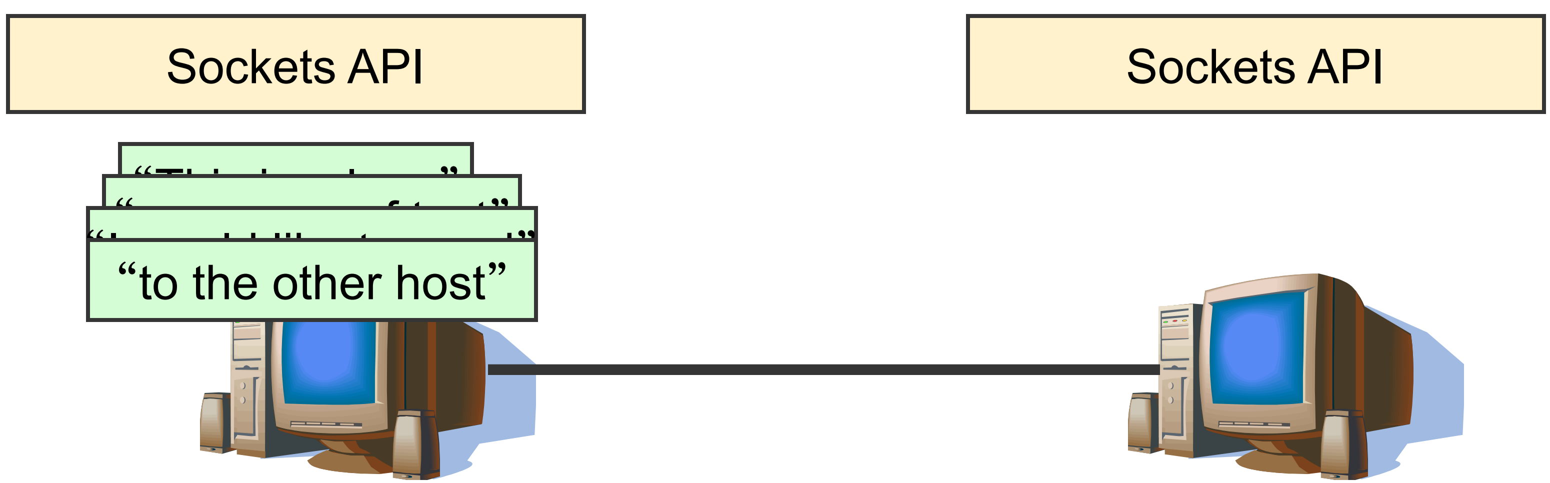
“This is a long sequence of text I would like to send to the other host”=**recv**(socket)



Datagram sockets

sendto(“This is a long”)
sendto(“sequence of text”)
sendto(“I would like to send”) **sendto**(“to the other host”)

“This is a long”=**recvfrom**(socket)
“sequence of text”=**recvfrom**(socket)
“I would like to send”=**recvfrom**(socket)
“to the other host”=**recvfrom**(socket)



What specific functions to expose?

- Data structures to store information about connections and hosts

Socket Address Structure

- IP address:

```
struct in_addr {
    in_addr_t s_addr;        /* 32-bit IP address */
};
```

- TCP or UDP address:

```
struct sockaddr_in {
    short sin_family;        /* e.g., AF_INET */
    ushort sin_port;         /* TCP/UDP port */
    struct in_addr;          /* IP address */
};
```

Structure: `addrinfo`

- The **`addrinfo`** data structure (from **`/usr/include/netdb.h`**)
  - Canonical domain name and aliases
  - List of addresses associated with machine
  - Also address type and length information

```
int ai_flags                  Input flags
int ai_family                 Address family of socket
int ai_socktype               Socket type
int ai_protocol               Protocol of socket
socklen_t ai_addrlen          Length of socket address
struct sockaddr *ai_addr      Socket address of socket
char *ai_canonname            Canonical name of service location
struct addrinfo *ai_next      Pointer to next in list
```

Address Access/Conversion Functions

```
#include <sys/types.h>
#include <sys/socket.h>
#include <netdb.h>
int getaddrinfo(const char *restrict node,
          const char *restrict service,
          const struct addrinfo *restrict hints,
          struct addrinfo **restrict res);
```

- Parameters
  - `node`: host name or IP address to connect to
  - `service`: a port number ("80") or the name of a service (found /etc/services: "http")
  - `hints`: a filled out struct addrinfo

Example: Server

```
int status;
struct addrinfo hints;
struct addrinfo *servinfo;                      // point to the results

memset(&hints, 0, sizeof hints);                // empty struct
hints.ai_family = AF_UNSPEC;                    // IPv4 or IPv6
hints.ai_socktype = SOCK_STREAM;                // TCP stream sockets
hints.ai_flags = AI_PASSIVE;                    // fill in my IP for me

if ((status = getaddrinfo(NULL, "3490", &hints, &servinfo)) != 0) {
    fprintf(stderr, "getaddrinfo error: %s\n", gai_strerror(status));
    exit(1);
}
// servinfo now points to a linked list of 1 or more struct addrinfos
// ... do everything until you don't need servinfo anymore ....

freeaddrinfo(servinfo);                         // free the linked-list
```

Example: `getaddrinfo`

```
int status;
struct addrinfo hints;
struct addrinfo *servinfo;              // pointer to results

memset(&hints, 0, sizeof hints);        // empty struct
hints.ai_family = AF_UNSPEC;            // don't care IPv4/IPv6
hints.ai_socktype = SOCK_STREAM;        // TCP stream sockets

// get ready to connect
status = getaddrinfo("www.example.net", "3490", &hints,
    &servinfo);

// servinfo now points to a linked list of 1 or more struct
    addrinfos
```

What specific functions to expose?

- Data structures to store information about connections and hosts
- Functions to create a socket

Function: `socket`

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

- Create a socket.
  - Returns file descriptor or -1. Also sets `errno` on failure.
  - `family`: address family (namespace)
    - `AF_INET` for IPv4
    - other possibilities: `AF_INET6` (IPv6), `AF_UNIX` or `AF_LOCAL` (Unix socket), `AF_ROUTE` (routing)
  - `type`: style of communication
    - `SOCK_STREAM` for TCP (with `AF_INET`)
    - `SOCK_DGRAM` for UDP (with `AF_INET`)
  - `protocol`: protocol within family
    - typically 0

Example: socket

```
int sockfd, new_fd; /* listen on sock_fd, new
                                              connection on
   new_fd */
struct sockaddr_in my_addr;       /* my address     */
struct sockaddr_in their_addr; /* connector addr */
int sin_size;

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

What specific functions to expose?

- Data structures to store information about connections and hosts
- Functions to create a socket
- Functions to establish connections

Function: `bind`

```
int bind (int sockfd, struct sockaddr*
   myaddr, int addrlen);
```

- Bind a socket to a local IP address and port number
  - Returns 0 on success, -1 and sets `errno` on failure
  - `sockfd`: socket file descriptor (returned from `socket`)
  - `myaddr`: includes IP address and port number
    - IP address: set by kernel if value passed is `INADDR_ANY`, else set by caller
    - port number: set by kernel if value passed is 0, else set by caller
  - `addrlen`: length of address structure
    - `= sizeof (struct sockaddr_in)`

TCP and UDP Ports

- Allocated and assigned by the Internet Assigned Numbers Authority
  - see `RFC 1700` (for historical purposes only)

1-512	standard services (see `/etc/services`) super-user only
513-1023	registered and controlled, also used for identity verification super-user only
1024-49151	registered services/ephemeral ports
49152-65535	private/ephemeral ports

Reserved Ports

Keyword	Decimal	Description	Keyword	Decimal	Description
-------	-------	-----------	-------	-------	-----------
	0/tcp	Reserved	time	37/tcp	Time
	0/udp	Reserved	time	37/udp	Time
tcpmux	1/tcp	TCP Port Service	name	42/tcp	Host Name Server
tcpmux	1/udp	TCP Port Service	name	42/udp	Host Name Server
echo	7/tcp	Echo	nameserver	42/tcp	Host Name Server
echo	7/udp	Echo	nameserver	42/udp	Host Name Server
systat	11/tcp	Active Users	nicname	43/tcp	Who Is
systat	11/udp	Active Users	nicname	43/udp	Who Is
daytime	13/tcp	Daytime (RFC 867)	domain	53/tcp	Domain Name Server
daytime	13/udp	Daytime (RFC 867)	domain	53/udp	Domain Name Server
qotd	17/tcp	Quote of the Day	whois++	63/tcp	whois++
qotd	17/udp	Quote of the Day	whois++	63/udp	whois++
chargen	19/tcp	Character Generator	gopher	70/tcp	Gopher
chargen	19/udp	Character Generator	gopher	70/udp	Gopher
ftp-data	20/tcp	File Transfer Data	finger	79/tcp	Finger
ftp-data	20/udp	File Transfer Data	finger	79/udp	Finger
ftp	21/tcp	File Transfer Ctl	http	80/tcp	World Wide Web HTTP
ftp	21/udp	File Transfer Ctl	http	80/udp	World Wide Web HTTP
ssh	22/tcp	SSH Remote Login	www	80/tcp	World Wide Web HTTP
ssh	22/udp	SSH Remote Login	www	80/udp	World Wide Web HTTP
telnet	23/tcp	Telnet	www-http	80/tcp	World Wide Web HTTP
telnet	23/udp	Telnet	www-http	80/udp	World Wide Web HTTP
smtp	25/tcp	Simple Mail Transfer	kerberos	88/tcp	Kerberos
smtp	25/udp	Simple Mail Transfer	kerberos	88/udp	Kerberos

Function: `listen`

`int listen (int sockfd, int backlog);`

- Put socket into passive state (wait for connections rather than initiate a connection)
  - Returns 0 on success, -1 and sets `errno` on failure
  - `sockfd`: socket file descriptor (returned from `socket`)
  - `backlog`: bound on length of unaccepted connection queue (connection backlog); kernel will cap, thus better to set high
  - Example:

```
if (listen(sockfd, BACKLOG) == -1) {
        perror("listen");
        exit(1);
}
```

Functions: `accept`

```
int accept (int sockfd, struct sockaddr* cliaddr,
    int* addrlen);
```

- Block waiting for a new connection
  - Returns file descriptor or -1 and sets `errno` on failure
  - `sockfd`: socket file descriptor (returned from `socket`)
  - `cliaddr`: IP address and port number of client (returned from call)
  - `addrlen`: length of address structure = pointer to `int` set to `sizeof (struct sockaddr_in)`
- `addrlen` is a **value-result** argument
  - the caller passes the size of the address structure, the kernel returns the size of the client's address (the number of bytes written)

Functions: accept

```
sin_size = sizeof(struct sockaddr_in);
if ((new_fd = accept(sockfd, (struct sockaddr*)
                &their_addr, &sin_size)) == -1) {
    perror("accept");
    continue;
}
```

- How does the server know which client it is?
  - `their_addr.sin_addr` contains the client's IP address
  - `their_addr.port` contains the client's port number

```
printf("server: got connection from %s\n",
        inet_ntoa(their_addr.sin_addr));
```

Functions: `accept`

- Notes
  - After `accept()` returns a new socket descriptor, I/O can be done using `read()` and `write()`
  - Why does `accept()` need to return a new descriptor?

Example: Server

```
my_addr.sin_family = AF_INET; /* host byte order */
my_addr.sin_port = htons(MYPORT); /* short, network
                                     byte order   */
my_addr.sin_addr.s_addr = htonl(INADDR_ANY);
/* automatically fill with my IP                 */
bzero(&(my_addr.sin_zero), 8);    /* zero struct */

if (bind(sockfd, (struct sockaddr *)&my_addr,
        sizeof(struct sockaddr)) == -1) {
    perror("bind");
    exit(1);
}
```

Example: Server

```
if (listen(sockfd, BACKLOG) == -1) {
    perror("listen");
    exit(1);
}

while(1) { /* main accept() loop */
    sin_size = sizeof(struct sockaddr_in);
    if ((new_fd = accept(sockfd, (struct sockaddr*)
                         &their_addr,&sin_size)) == -1) {
            perror("accept");
            continue;
    }
    printf("server: got connection from %s\n",
    inet_ntoa(their_addr.sin_addr));
```

Function: `connect`

```
int connect (int sockfd, struct
   sockaddr* servaddr, int addrlen);
```

- Connect to another socket.
  - Returns 0 on success, -1 and sets `errno` on failure
  - `sockfd`: socket file descriptor (returned from `socket`)
  - `servaddr`: IP address and port number of server
  - `addrlen`: length of address structure
    - `= sizeof (struct sockaddr_in)`
- Can use with UDP to restrict incoming datagrams and to obtain asynchronous errors

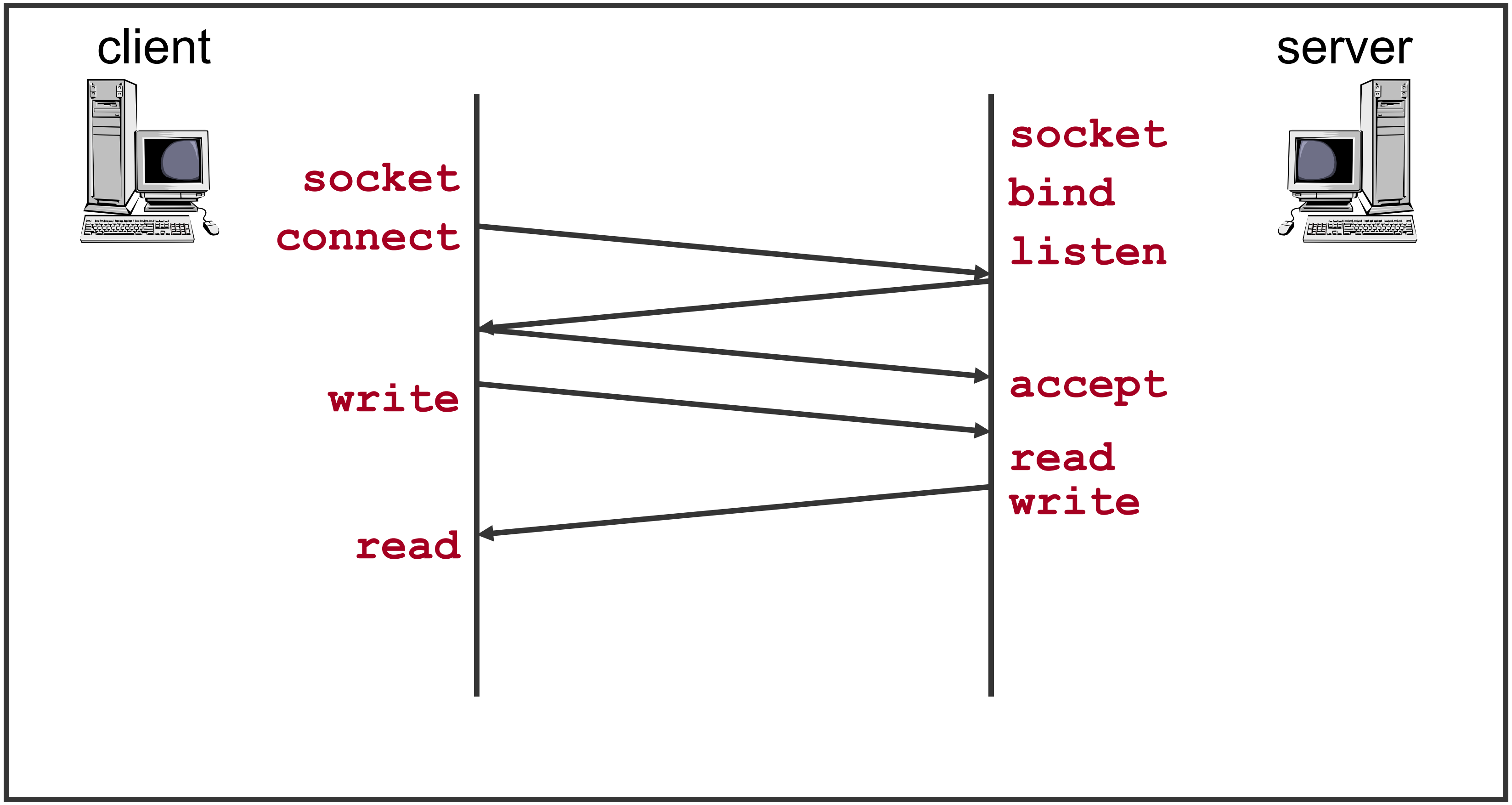
Example: Client

```
their_addr.sin_family = AF_INET; /* interp'd by host */
their_addr.sin_port = htons (PORT);
their_addr.sin_addr = *((struct in_addr*)he->h_addr);
bzero (&(their_addr.sin_zero), 8);
/* zero rest of struct */
if (connect (sockfd, (struct sockaddr*)&their_addr,
             sizeof (struct sockaddr)) == -1) {
    perror ("connect");
    exit (1);
}
```

What specific functions to expose?

- Data structures to store information about connections and hosts
- Functions to create a socket
- Functions to establish connections
- Functions to send and receive data

TCP Connection Example



Functions: `write`

```
int write (int sockfd, char* buf, size_t nbytes);
```

- Write data to a stream (TCP) or "connected" datagram (UDP) socket
  - Returns number of bytes written or -1 and sets `errno` on failure
  - `sockfd`: socket file descriptor (returned from `socket`)
  - `buf`: data buffer
  - `nbytes`: number of bytes to try to write
  - Example:

```
if((w = write(fd, buf, sizeof(buf))) < 0) {
    perror("write");
    exit(1);
}
```

Functions: `write`

```
int write (int sockfd, char* buf, size_t nbytes);
```

- Notes
  - `write` blocks waiting for data from the client
  - `write` may not write all bytes asked for
    - Does not guarantee that `sizeof(buf)` is written
    - This is not an error
    - Simply continue writing to the device
  - Some reasons for failure or partial writes
    - Process received interrupt or signal
    - Kernel resources unavailable (*e.g.*, buffers)

Example: **writen**

```
/* Write "n" bytes to a descriptor */
ssize_t writen(int fd, const void *ptr, size_t n) {
    size_t nleft;
    ssize_t nwritten;
    nleft = n;
    while (nleft > 0) {
        if ((nwritten = write(fd, ptr, nleft)) < 0) {
            if (nleft == n)
                return(-1); /* error, return -1 */
            else
                break; /* error, return amount written so far */
        }
        else
            if (nwritten == 0)
                break;
        nleft -= nwritten;
        ptr += nwritten;
    }
    return(n - nleft); /* return >= 0 */
}
```

write returned a potential error

0 bytes were written

Update number of bytes left to write and pointer into buffer

Functions: `send`

```
int send(int sockfd, const void * buf, size_t
    nbytes, int flags);
```

- Send data on a stream (TCP) or “connected” datagram (UDP) socket
  - Returns number of bytes written or -1 and sets `errno` on failure
  - `sockfd`: socket file descriptor (returned from `socket`)
  - `buf`: data buffer
  - `nbytes`: number of bytes to try to write
  - `flags`: control flags
    - MSG_PEEK: get data from the beginning of the receive queue without removing that data from the queue
- Example

```
len = strlen(msg);
bytes_sent = send(sockfd, msg, len, 0);
```

Functions: `read`

```
int read (int sockfd, char* buf, size_t nbytes);
```

- Read data from a stream (TCP) or "connected" datagram (UDP) socket
  - Returns number of bytes read or -1, sets `errno` on failure
  - Returns 0 if socket closed
  - `sockfd`: socket file descriptor (returned from `socket`)
  - `buf`: data buffer
  - `nbytes`: number of bytes to try to read
  - Example

```
if((r = read(newfd, buf, sizeof(buf))) < 0) {
    perror("read"); exit(1);
}
```

Functions: `read`

```
int read (int sockfd, char* buf, size_t nbytes);
```

- Notes
  - `read` blocks waiting for data from the client
  - `read` may return less than asked for
    - Does not guarantee that `sizeof(buf)` is read
    - This is not an error
    - Simply continue reading from the device

Example: `readn`

```
/* Read "n" bytes from a descriptor */
ssize_t readn(int fd, void *ptr, size_t n) {
    size_t nleft;
    ssize_t nread;
    nleft = n;
    while (nleft > 0) {
        if ((nread = read(fd, ptr, nleft)) < 0) {
            if (nleft == n)
                return(-1); /* error, return -1 */
            else
                break; /* error, return amt read */
        }
        else
            if (nread == 0)
                break; /* EOF */
            nleft -= nread;
            ptr += nread;
    }
    return(n - nleft); /* return >= 0 */
}
```

read returned a potential error

0 bytes were read

Update number of bytes left to read and pointer into buffer

Functions: `recv`

```
int recv(int sockfd, void *buf, size_t nbytes,
   int flags);
```

- Read data from a stream (TCP) or “connected” datagram (UDP) socket
  - Returns number of bytes read or -1, sets `errno` on failure
  - Returns 0 if socket closed
  - `sockfd`: socket file descriptor (returned from `socket`)
  - `buf`: data buffer
  - `nbytes`: number of bytes to try to read
  - `flags`: see man page for details; typically use 0

Functions: `recv`

`int read (int sockfd, char* buf, size_t nbytes);`

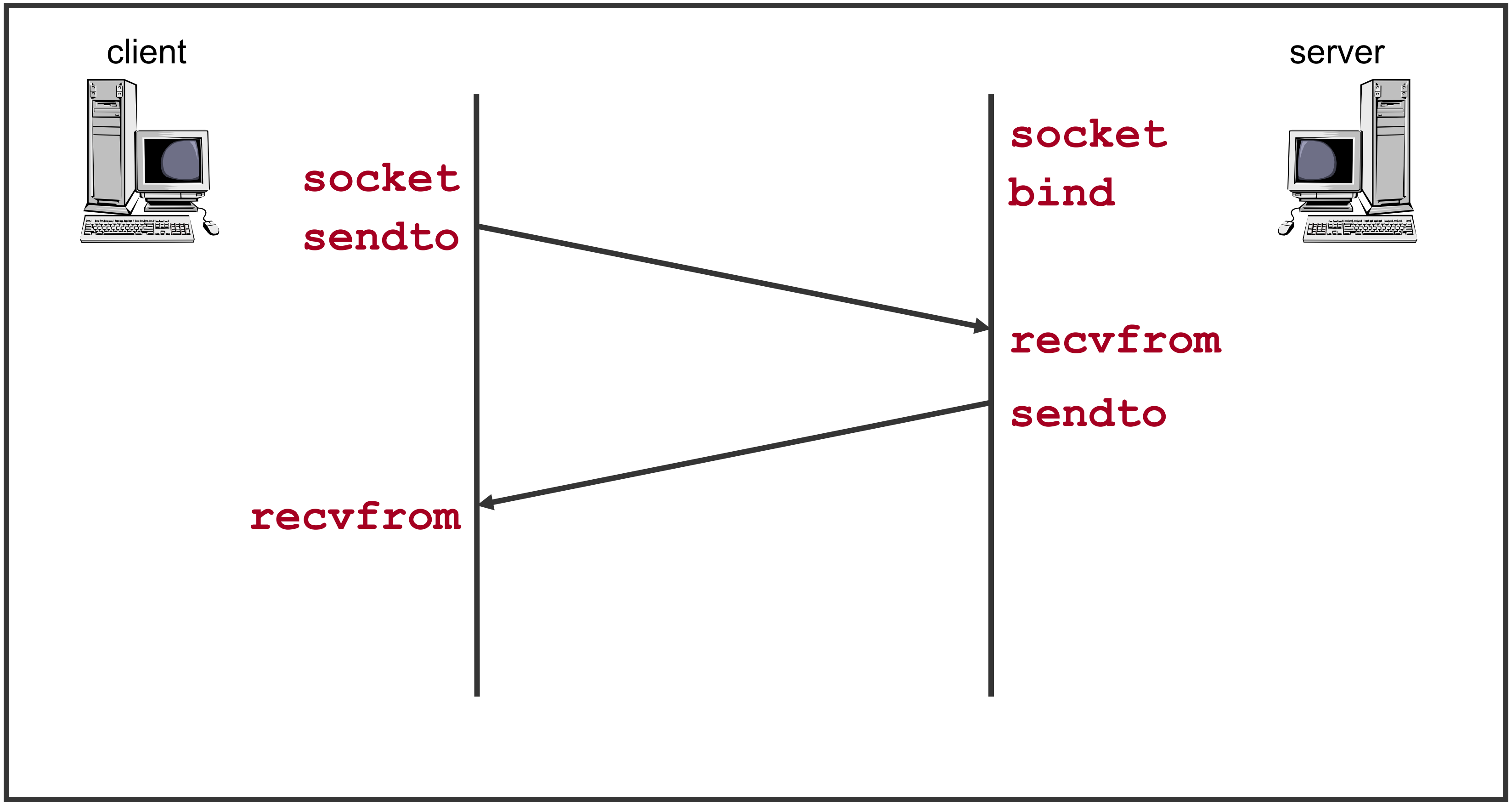
- Notes
  - `read` blocks waiting for data from the client but does not guarantee that `sizeof(buf)` is read
  - Example

```
if((r = read(newfd, buf, sizeof(buf))) < 0) {
   perror("read"); exit(1);
}
```

Sending and Receiving Data

- Datagram sockets aren't connected to a remote host
  - What piece of information do we need to give before we send a packet?
  - The destination/source address!

UDP Connection Example



Functions: `sendto`

```
int sendto (int sockfd, char* buf, size_t nbytes,
    int flags, struct sockaddr* destaddr, int
    addrlen);
```

- Send a datagram to another UDP socket
  - Returns number of bytes written or -1 and sets `errno` on failure
  - `sockfd`: socket file descriptor (returned from `socket`)
  - `buf`: data buffer
  - `nbytes`: number of bytes to try to read
  - `flags`: see man page for details; typically use 0
  - `destaddr`: IP address and port number of destination socket
  - `addrlen`: length of address structure
    - `= sizeof (struct sockaddr_in)`

Functions: `sendto`

```
int sendto (int sockfd, char* buf, size_t nbytes,
   int flags, struct sockaddr* destaddr, int
   addrlen);
```

- Example

```
n = sendto(sock, buf, sizeof(buf), 0,(struct
     sockaddr *) &from,fromlen);
if (n < 0)
     perror("sendto");
     exit(1);
}
```

Functions: `recvfrom`

```
int recvfrom (int sockfd, char* buf, size_t
    nbytes, int flags, struct sockaddr* srcaddr,
    int* addrlen);
```

- Read a datagram from a UDP socket.
  - Returns number of bytes read (0 is valid) or -1 and sets **`errno`** on failure
  - **`sockfd`**: socket file descriptor (returned from **`socket`**)
  - **`buf`**: data buffer
  - **`nbytes`**: number of bytes to try to read
  - **`flags`**: see man page for details; typically use 0
  - **`srcaddr`**: IP address and port number of sending socket (returned from call)
  - **`addrlen`**: length of address structure = pointer to **`int`** set to **`sizeof (struct sockaddr_in)`**

Functions: `recvfrom`

```
int recvfrom (int sockfd, char* buf, size_t
   nbytes, int flags, struct sockaddr* srcaddr,
   int* addrlen);
```

- Example

```
n = recvfrom(sock, buf, 1024, 0, (struct sockaddr
    *)&from,&fromlen);
if (n < 0) {
    perror("recvfrom");
    exit(1);
}
```

What specific functions to expose?

- Data structures to store information about connections and hosts
- Functions to create a socket
- Functions to establish connections
- Functions to send and receive data
- Functions to teardown connections

Functions: `close`

```
int close (int sockfd);
```

- Close a socket
  - Returns 0 on success, -1 and sets `errno` on failure
  - `sockfd`: socket file descriptor (returned from `socket`)

- Closes communication on socket in both directions
  - All data sent before `close` are delivered to other side (although this aspect can be overridden)
- After `close`, `sockfd` is not valid for reading or writing

Functions: `shutdown`

```
int shutdown (int sockfd, int howto);
```

- Force termination of communication across a socket in one or both directions
  - Returns 0 on success, -1 and sets `errno` on failure
  - `sockfd`: socket file descriptor (returned from `socket`)
  - `howto`:
    - `SHUT_RD` to stop reading
    - `SHUT_WR` to stop writing
    - `SHUT_RDWR` to stop both
- `shutdown` overrides the usual rules regarding duplicated sockets, in which TCP teardown does not occur until all copies have closed the socket

Note on `close` vs. `shutdown`

- `close()`: closes the socket but the connection is still open for processes that shares this socket
  - The connection stays opened both for read and write
- `shutdown()`: breaks the connection for all processes sharing the socket
  - A read will detect `EOF`, and a write will receive `SIGPIPE`
  - `shutdown()` has a second argument how to close the connection:
    - 0 means to disable further reading
    - 1 to disable writing
    - 2 disables both

One tricky issue…

- Different processor architectures store data in different “byte orderings”
  - What is 200 in binary?
  - `1100 1001`?

    or
  - `1001 1100`?

One tricky issue…

- Big Endian vs. Little Endian
  - Little Endian (Intel, DEC):
    - Least significant byte of word is stored in the lowest memory address
  - Big Endian (Sun, SGI, HP, PowerPC):
    - Most significant byte of word is stored in the lowest memory address
  - Example: `128.2.194.95`

Big Endian	128	2	194	95
Little Endian	95	194	2	128

One tricky issue…

- Big Endian vs. Little Endian
  - Network Byte Order = Big Endian
    - Allows both sides to communicate
    - Must be used for some data (i.e. IP Addresses)
  - What about ordering within bytes?
    - Most modern processors agree on ordering within bytes

Converting byte orderings

Solution: use byte ordering functions to convert.

```
int m, n;
short int s,t;

m = ntohl (n)   net-to-host long (32-bit) translation
s = ntohs (t)   net-to-host short (16-bit) translation
n = htonl (m)   host-to-net long (32-bit) translation
t = htons (s)   host-to-net short (16-bit) translation
```

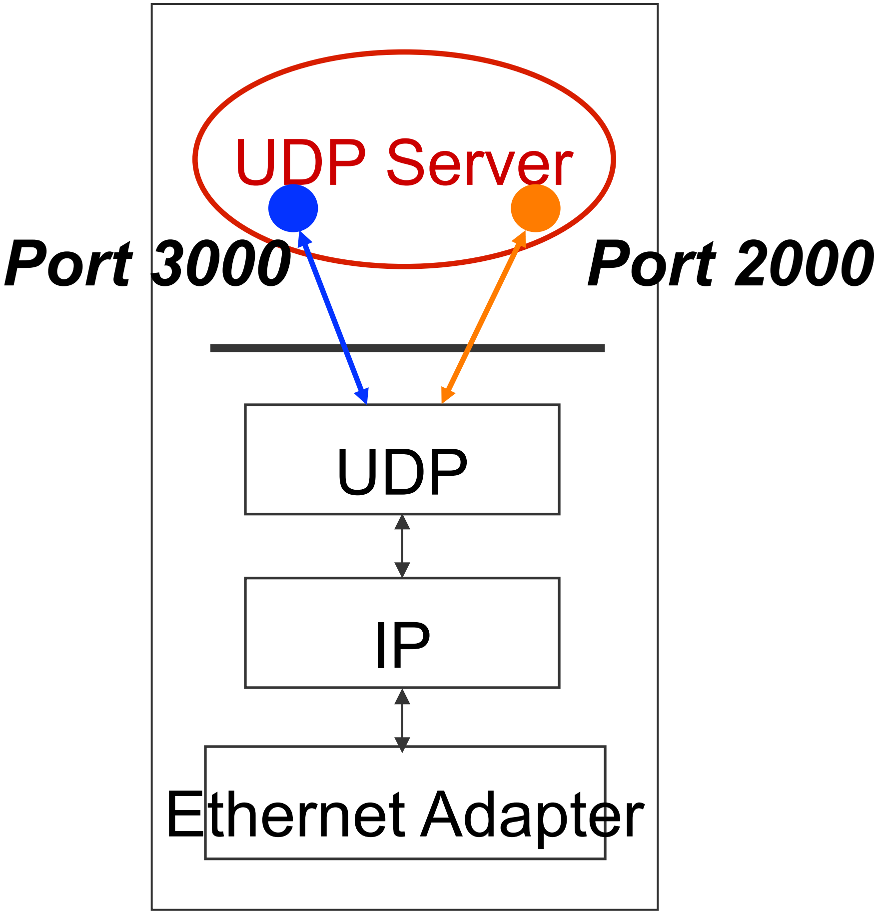
Why Can't Sockets Hide These Details?

- Dealing with endian differences is tedious
  - Couldn't the socket implementation deal with this
  - … by swapping the bytes as needed?
- No, swapping depends on the data type
  - Two-byte short int: (byte 1, byte 0) vs. (byte 0, byte 1)
  - Four-byte long int: (byte 3, byte 2, byte 1, byte 0) vs. (byte 0, byte 1, byte 2, byte 3)
  - String of one-byte charters: (char 0, char 1, char 2, …) in both cases
- Socket layer doesn't know the data types
  - Sees the data as simply a buffer pointer and a length
  - Doesn't have enough information to do the swapping

How to handle concurrency?

- Process requests serially
  - Slow – what if you're processing another request? What if you're blocked on `read()`?

A UDP Server



- How can a UDP server service multiple ports simultaneously?

UDP Server: Servicing Two Ports

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

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

while(1) {
    recvfrom(s1, buf, sizeof(buf), ...);
    /* process buf */
    recvfrom(s2, buf, sizeof(buf), ...);
    /* process buf */
}
```

What problems does this code have?

How to handle concurrency?

- Process requests serially
  - Slow – what if you're processing another request? What if you're blocked on `accept()`?
- Multiple threads/processes (e.g. Apache, Chrome)
  - Each thread/process handles one request
  - `fork()`, `pthreads`
- Synchronous I/O (e.g. Squid web proxy cache)
  - Maintain a "set" of file descriptors, whenever one has an "event", process it and put it back onto the set
  - `select()`, `poll()`

Select

```
int select (int num_fds, fd_set* read_set, fd_set*
    write_set, fd_set* except_set, struct timeval*
    timeout);
```

- Wait for readable/writable file descriptors.
- Return:
  - Number of descriptors ready
  - -1 on error, sets **`errno`**
- Parameters:
  - **`num_fds`**:
    - number of file descriptors to check, numbered from 0
  - **`read_set`**, **`write_set`**, **`except_set`**:
    - Sets (bit vectors) of file descriptors to check for the specific condition
  - **`timeout`**:
    - Time to wait for a descriptor to become ready

File Descriptor Sets

```
int select (int num_fds, fd_set* read_set,
   fd_set* write_set, fd_set* except_set, struct
   timeval* timeout);
```

- Bit vectors
  - Only first `num_fds` checked
  - Macros to create and check sets

```
fds_set myset;
void FD_ZERO (&myset);      /* clear all bits */
void FD_SET (n, &myset);    /* set bits n to 1 */
void FD_CLEAR (n, &myset);  /* clear bit n */
int FD_ISSET (n, &myset);   /* is bit n set? */
```

File Descriptor Sets

- Three conditions to check for
  - Readable:
    - Data available for reading
  - Writable:
    - Buffer space available for writing
  - Exception:
    - Out-of-band data available (TCP)

Building Timeouts with Select and Poll

- Time structure

Number of seconds since midnight, January 1, 1970 GMT

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

unix will have its own "Y2K" problem one second after 10:14:07pm, Monday January 18, 2038 (will appear to be 3:45:52pm, Friday December 13, 1901)

Select

- High-resolution sleep function
  - All descriptor sets `NULL`
  - Positive `timeout`
- Wait until descriptor(s) become ready
  - At least one descriptor in set
  - `timeout` `NULL`
- Wait until descriptor(s) become ready or timeout occurs
  - At least one descriptor in set
  - Positive `timeout`
- Check descriptors immediately (poll)
  - At least one descriptor in set
  - 0 `timeout`

Which file descriptors are set and what should the timeout value be?

Select: Example

```
fd_set my_read;
FD_ZERO(&my_read);
FD_SET(0, &my_read);

if (select(1, &my_read, NULL, NULL) == 1) {
   assert(FD_ISSET(0, &my_read);
   /* data ready on stdin */
}
```

What went wrong: after select indicates data available on a connection, read returns no data?

Select: Timeout Example

```
I nt main(void) {
    struct timeval tv;
    fd_set readfds;
    tv.tv_sec = 2;
    tv.tv_usec = 500000;
    FD_ZERO(&readfds);
    FD_SET(STDIN, &readfds);
    // don't care about writefds and exceptfds:
    select(1, &readfds, NULL, NULL, &tv);
    if (FD_ISSET(STDIN, &readfds))
        printf("A key was pressed!\n");
    else
        printf("Timed out.\n");
    return 0;
}
```

Wait 2.5 seconds for something to appear on standard input

`select()` vs. `poll()`

Which to use?

- BSD-family (e.g., FreeBSD, MacOS)
  - `poll()` just calls `select()` internally
- System V family (e.g., AT&T Unix)
  - `select()` just calls `poll()` internally

Concurrent programming with Posix Threads (pthreads)

- Thread management
  - Creating, detaching, joining, etc. Set/ query thread attributes
- Mutexes
  - Synchronization
- Condition variables
  - Communications between threads that share a mutex

Creating a Thread

```
int pthread_create (pthread_t* tid,
    pthread_attr_t* attr, void*(child_main), void*
    arg);
```

- `pthread_create()` takes a pointer to a function as one of its arguments
  - `child_main` is called with the argument specified by `arg`
  - `child_main` can only have one parameter of type `void *`
  - Complex parameters can be passed by creating a structure and passing the address of the structure
  - The structure can't be a local variable

Example: pthreads

```
#include <pthread.h>
#define NUM_THREADS 5

void *PrintHello(void *threadid) {
        printf("\n%d: Hello World!\n", threadid);
        pthread_exit(NULL);
}

int main (int argc, char *argv[]) {
    pthread_t threads[NUM_THREADS];
    int rc, t;

    for(t=0;t < NUM_THREADS;t++) {
        printf("Creating thread %d\n", t);
        rc = pthread_create(&threads[t], NULL, PrintHello, (void *)t);
        if (rc) {
           printf("ERROR; pthread_create() return code is %d\n", rc);
           exit(-1);
        }
    }
    pthread_exit(NULL);
}
```

Example: `pthread_join()`

```
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>
#define NUM_THREADS 4

int main (int argc, char *argv[]) {
   pthread_t thread[NUM_THREADS];
   pthread_attr_t attr;
   int rc;
   long t;
   void *status;
```

```
/* Initialize and set thread detached
   attribute */
pthread_attr_init(&attr);
pthread_attr_setdetachstate(&attr,
   PTHREAD_CREATE_JOINABLE);

for(t=0; t<NUM_THREADS; t++) {
   printf("Main: creating thread %ld\n", t);
   rc = pthread_create(&thread[t], &attr,
        BusyWork, (void *)t);
   if (rc) {
      printf("ERROR; return code is %d\n",
             rc);
      exit(-1);
      }
   }
/* Free attributes */
pthread_attr_destroy(&attr);
```

Example: pthread_join()

```
void *BusyWork(void *t) {
   int i;
   long tid;
   double result = 0.0;
   tid = (long)t;
   printf("Thread %ld starting...\n",
      tid);
   for (i=0; i<1000000; i++) {
      result = result + sin(i) * tan(i);
   }
   printf("Thread %ld result = %e\n",
      tid, result);
   pthread_exit((void*) t);
}
```

```
int main (int argc, char *argv[]) {
...

   /* Wait for the other threads */
   for(t=0; t<NUM_THREADS; t++) {
      rc = pthread_join(thread[t], &status);
      if (rc) {
         printf("ERROR; return code is %d\n", rc);
         exit(-1);
      }
      printf("Main: status for thread %ld: %ld\n",
            t, (long)status);
   }

   printf("Main: program completed. Exiting.\n");
   pthread_exit(NULL);
}
```

Using pthreads

- When coding
  - Include `<pthread.h>` first in all source files
- When compiling
  - Use compiler flag `–D_REENTRANT`
- When linking
  - Link library `-lpthread`

pthread Error Handling

- pthreads functions do not follow the usual Unix conventions
  - Similarity
    - Returns 0 on success
  - Differences
    - Returns error code on failure
    - Does not set `errno`
  - What about `errno`?
    - Each thread has its own
    - Define `_REENTRANT` (`-D_REENTRANT` switch to compiler) when using pthreads