Lecture 2: Introduction to Unix Network Programming

Reference: Stevens Unix Network Programming
Internet Protocols

- Application Layers
  - FTP
  - HTTP
  - Video
  - Audio
- Transport
  - TCP
  - UDP
- Network
  - IP
- Data Link
  - Ethernet
  - WLAN
  - 4G
  - WiFi
- Physical
Direction and Principles

- Programming
  - learn to use Internet for communication (with focus on implementation of networking concepts)
- Principles and Concepts
  - learn to build network from ground up

Levels:
- Transport
- Network
- Data Link
- Physical
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
  - De facto standard for network programming
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?

- Use Transport 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

```
Client

“GET index.html”
(request for web page)

Web server

“HTTP/1.0 200 OK…”
(response, including web page)
```

- 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

Can you think of any network apps that are not client/server?
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

Which one is best?
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

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

\texttt{recv(socket)}

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

Sockets API

Sockets API
Datagram sockets

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

\texttt{“This is a long”=recvfrom(socket)}
\texttt{“sequence of text”=recvfrom(socket)}
\texttt{“I would like to send”=recvfrom(socket)}
\texttt{“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:**
  ```c
  struct in_addr {
      in_addr_t s_addr; /* 32-bit IP address */
  }
  ```

- **TCP or UDP address:**
  ```c
  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

```c
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

```c
#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

```c
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`

```c
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`

```c
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`

```c
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);
}
```
Example: **socket**

```c
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) {
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    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
TCP Connection Setup

client

socket
connect

Synchronize (SYN) J

SYN K, acknowledge (ACK) J+1

acknowledge (ACK) K+1

connect completes

server

socket
bind
listen

connection moved to complete queue

connection added to incomplete queue

accept
**Function: bind**

```c
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)

<table>
<thead>
<tr>
<th>Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-512</td>
<td>standard services (see /etc/services)</td>
</tr>
<tr>
<td></td>
<td>super-user only</td>
</tr>
<tr>
<td>513-1023</td>
<td>registered and controlled, also used for identity verification</td>
</tr>
<tr>
<td></td>
<td>super-user only</td>
</tr>
<tr>
<td>1024-49151</td>
<td>registered services/ephemeral ports</td>
</tr>
<tr>
<td>49152-65535</td>
<td>private/ephemeral ports</td>
</tr>
</tbody>
</table>
### Reserved Ports

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

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

```c
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

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

```c
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

```c
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`

```c
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

```c
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

client

socket
connect
write
read

server

socket
bind
listen
accept
read
write
Functions: \texttt{write}

\begin{verbatim}
int write (int sockfd, char* buf, size_t nbytes);
\end{verbatim}

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

\begin{verbatim}
if((w = write(fd, buf, sizeof(buf))) < 0) {
    perror(“write”);
    exit(1);
}
\end{verbatim}
Functions: **write**

```c
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: **written**

```c
/* Write "n" bytes to a descriptor */
ssize_t written(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`

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

- Send data un 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**
  ```c
  len = strlen(msg);
  bytes_sent = send(sockfd, msg, len, 0);
  ```
Functions: **read**

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

```c
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`

```c
/* 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: \texttt{recv}

\begin{verbatim}
int recv(int sockfd, void *buf, size_t nbytes, int flags);
\end{verbatim}

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

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

\begin{verbatim}
int sendto (int sockfd, char* buf, size_t nbytes, int flags, struct sockaddr* destaddr, int addrlen);
\end{verbatim}

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

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

**Example**

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

```c
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`

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

- **Example**
  ```c
  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`

```c
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`

```c
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

<table>
<thead>
<tr>
<th>128</th>
<th>2</th>
<th>194</th>
<th>95</th>
</tr>
</thead>
<tbody>
<tr>
<td>95</td>
<td>194</td>
<td>2</td>
<td>128</td>
</tr>
</tbody>
</table>

Where did the term “endian” come from?
One tricky issue...

- Big Endian vs. Little Endian: which should we use for networked communication?
  - 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.

```c
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
  // host-to-net short (16-bit) translation
```

Spring 2016
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
Problem: Socket at other end is closed

- Write to your end generates **SIGPIPE**
- This signal kills the program by default!

```c
signal (SIGPIPE, SIG_IGN);
```

- Call at start of main in server
- Allows you to ignore broken pipe signals
- Can ignore or install a proper signal handler
- Default handler exits (terminates process)
Advanced Sockets

Problem: How come I get "address already in use" from bind()?

- You have stopped your server, and then restarted it right away
- The sockets that were used by the first incarnation of the server are still active
Advanced Sockets:

**setsockopt**

```c
int yes = 1;
setsockopt (fd, SOL_SOCKET, 
  SO_REUSEADDR, (char *) &yes, sizeof (yes));
```

- Call just before `bind()`
- Allows bind to succeed despite the existence of existing connections in the requested TCP port
- Connections in limbo (e.g. lost final ACK) will cause bind to fail
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

```c
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()`
```c
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

```c
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

```c
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 \texttt{NULL}
  - Positive \texttt{timeout}
- Wait until descriptor(s) become ready
  - At least one descriptor in set
  - \texttt{timeout NULL}
- Wait until descriptor(s) become ready or timeout occurs
  - At least one descriptor in set
  - Positive \texttt{timeout}
- Check descriptors immediately (poll)
  - At least one descriptor in set
  - 0 \texttt{timeout}

Which file descriptors are set and what should the timeout value be?
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 */
}
Wait 2.5 seconds for something to appear on standard input

```c
int 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;
}
```
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

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

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

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

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

Example: \texttt{pthread_join()}

```c
#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()`

```c
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

- pthread 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
Summary

- Unix Network Programming
  - Transport protocols
    - TCP, UDP
  - Network programming
    - Sockets API, pthreads

- Next
  - Probability refresher
  - Direct link networks