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CMPSC 311 - Introduction to Systems Programming

Network Programming

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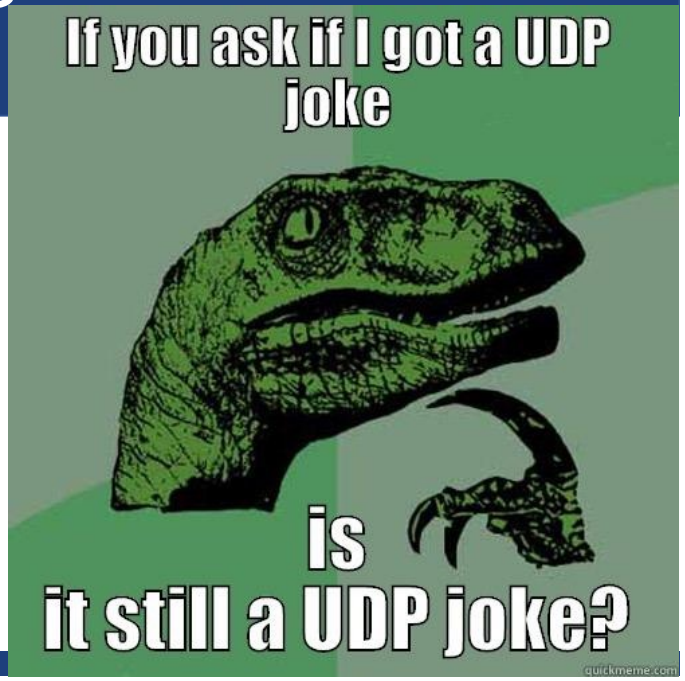
Slides are mostly by *Professor Patrick McDaniel* and *Professor Abutalib Aghayev*)



What is a network?

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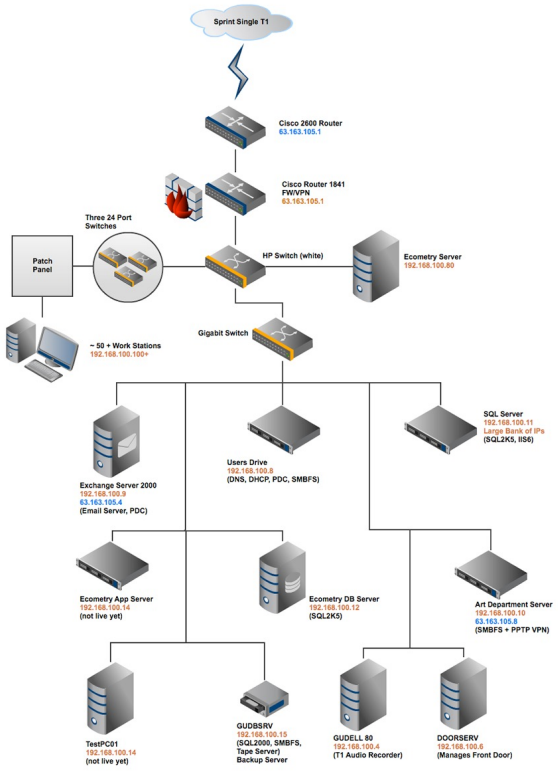
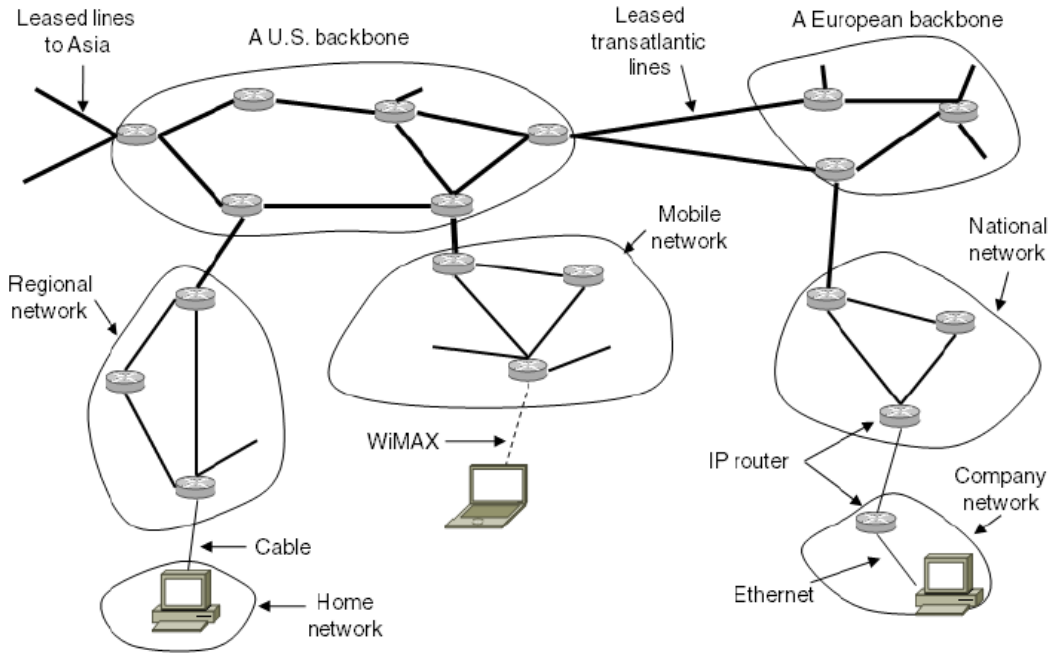
- A network is a collection of computing devices that share a transmission media
  - Traditional wired networks (ethernet)
  - High-speed backbone (fibre)
  - Wireless (radio)
  - Microwave
  - Infrared



- The way the network is organized is called the network topology

The Internet

The Internet is an interconnected collection of many networks.



Internet protocol stack (TCP/IP)

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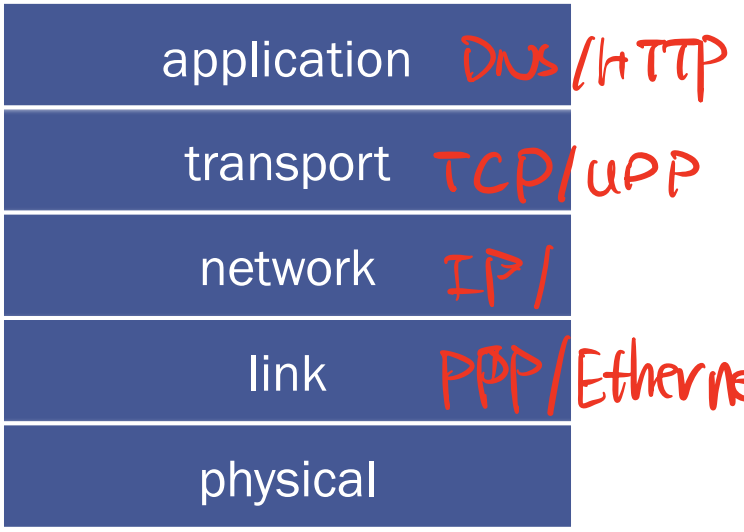
- application: supporting network applications
  - FTP, SMTP, HTTP, DNS
- transport: process-process data transfer
  - TCP, UDP
- network: routing of datagrams from source to destination
  - IP, routing protocols
- link: data transfer between neighboring network elements
  - PPP, Ethernet
- physical: bits "on the wire"



Network vs. Web

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- The network is a service …
  - A conduit for data to be passed between systems.
  - Layers services (generally) to allow flexibility.
  - Highly scalable.
  - This is a public channel.

- The Web is an application
  - This is an application for viewing/manipulating content.
  - This can either be public (as in CNN's website), or private (as in enterprise internal HR websites).

Networks Systems

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- Conceptually, think about network programming as two or more programs on the same or different computers talking to each other
  - The send messages back and forth
  - The "flow" of messages and the meaning of the message content is called the network protocol or just protocol

What's a Protocol?

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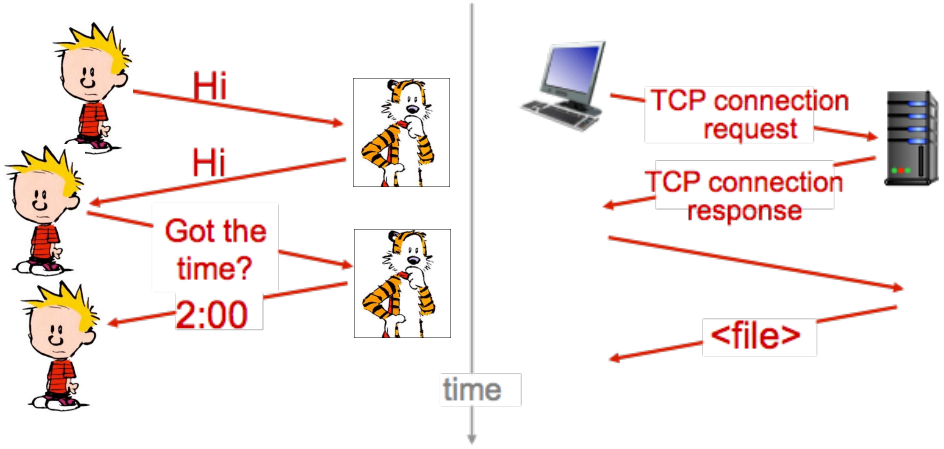
- Example: A human protocol and a computer protocol:



- Question: What are some other human protocols?

Socket Programming

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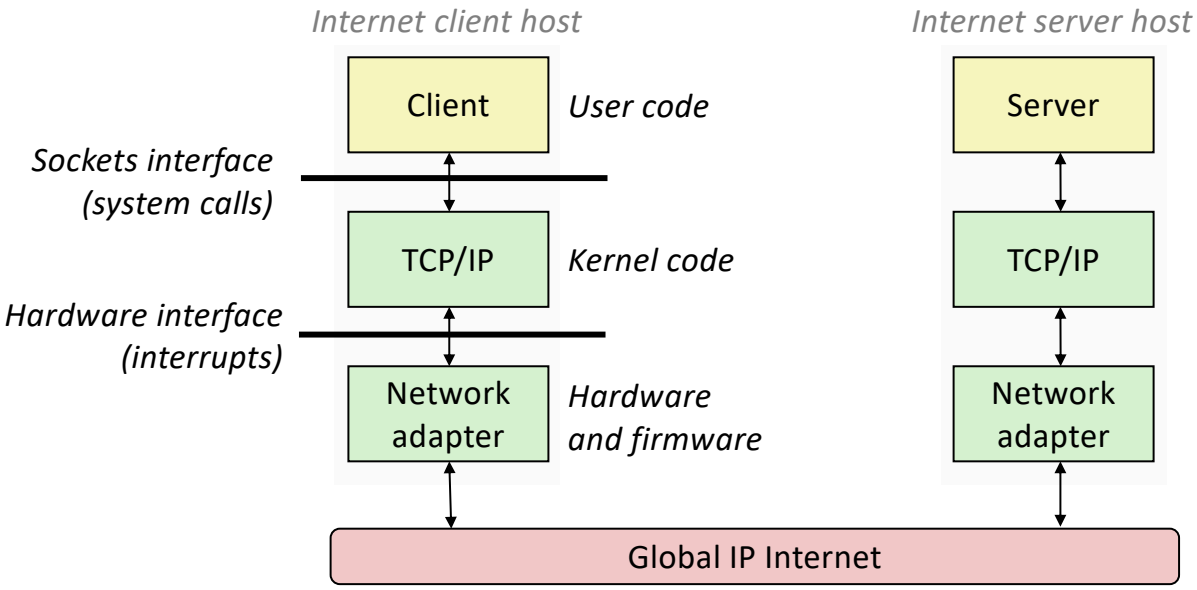
- Almost all meaningful careers in programming involve at least some level of network programming.
- Most of them involve sockets programming
  - Berkeley sockets originated in 4.2 BSD Unix circa 1983
    - it is the standard API for network programming
    - available on most OSs
  - POSIX socket API
    - a slight updating of the Berkeley sockets API
    - a few functions were deprecated or replaced
    - better support for multi-threading was added

Hardware and Software Organization of Internet Application



- Bryant and O'Hallaron, Computer Systems: A Programmer's Approach

IP addresses

- Every device on the Internet needs to have an address
  - Needs to be unique to make sure that it can be reached
- For IPv4, an IP address is a 4-byte tuple
  - e.g., 128.95.4.1 (80:5f:04:01 in hex)
- For IPv6, an IP address is a 16-byte tuple
  - e.g., 2d01:0db8:f188:0000:0000:0000:0000:1f33
    - 2d01:0db8:f188::1f33 in shorthand

A Programmer's View of the Internet

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- Hosts are mapped to a set of 32-bit IP Address
  - 146.186.145.12

- The set of IP addresses mapped to a set of identifiers called Internet domain names
  - 146.186.145.12 is mapped to www.eecs.psu.edu

- A process on one Internet host can communicate with a process on another Internet host over a connection

Recall file descriptors

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- Remember open, read, write, and close?
  - POSIX system calls interacting with files
  - recall `open()` returns a file descriptor
    - an integer that represents an open file
    - inside the OS, it's an index into a table that keeps track of any state associated with your interactions, such as the file position
    - you pass the file descriptor into read, write, and close

Networks and sockets

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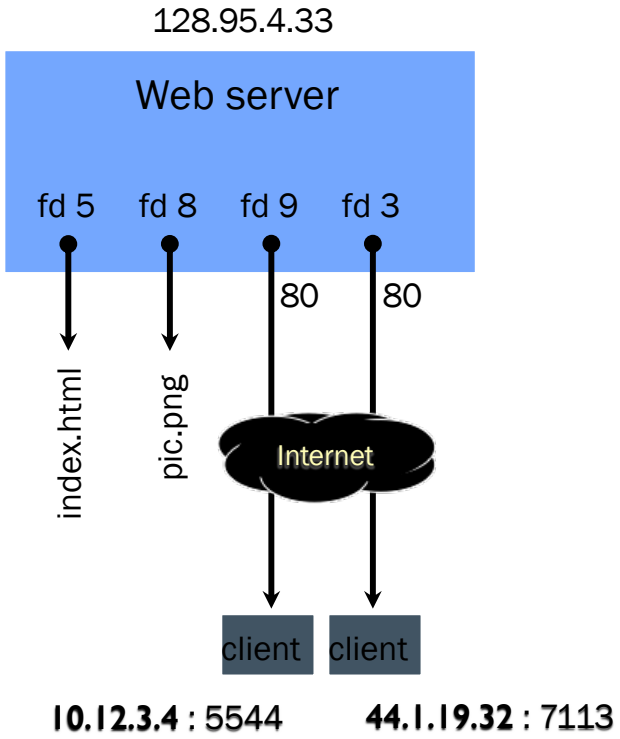
- UNIX makes all I/O look like file I/O
  - the good news is that you can use `read()` and `write()` to interact with remote computers over a network!
  - just like with files....
    - A program can have multiple network channels open at once
    - you need to pass `read()` and `write()` a file descriptor to let the OS know which network channel you want to write to or read from
  - The file descriptor used for network communications is a socket

Pictorially



file descriptor	type	connected to?
0	pipe	stdin (console)
1	pipe	stdout (console)
2	pipe	stderr (console)
3	TCP socket	local: 128.95.4.33:80 remote: 44.1.19.32:7113
5	file	index.html
8	file	pic.png
9	TCP socket	local: 128.95.4.33:80 remote: 10.12.3.4:5544

OS's descriptor table

Types of sockets

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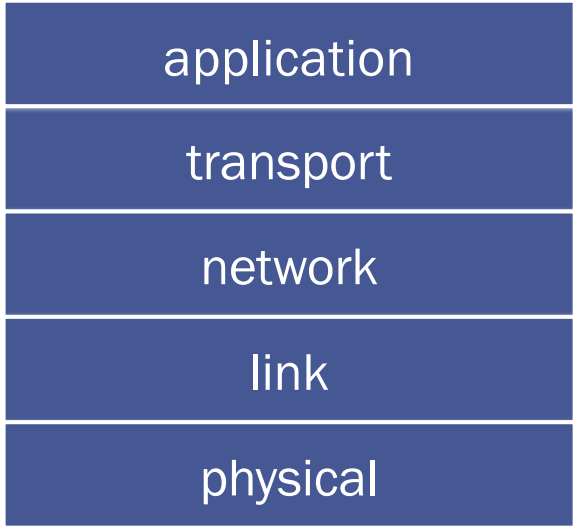
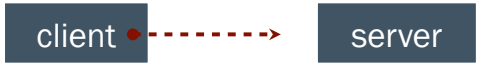
- Stream sockets
  - for connection-oriented, point-to-point, reliable bytestreams
    - uses TCP, SCTP, or other stream transports
- Datagram sockets
  - for connection-less, one-to-many, unreliable packets
    - uses UDP or other packet transports
- Raw sockets
  - for layer-3 communication (raw IP packet manipulation)

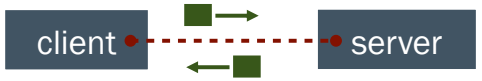


Stream (TCP) sockets

- Typically used for client / server communications
  - but also for other architectures, like peer-to-peer
- Client
  - an application that establishes a connection to a server
- Server
  - an application that receives connections from clients



1. establish connection



2. communicate

3. close connection

connection-less
one-to many
unreliable byte streams

Datagram (UDP) sockets

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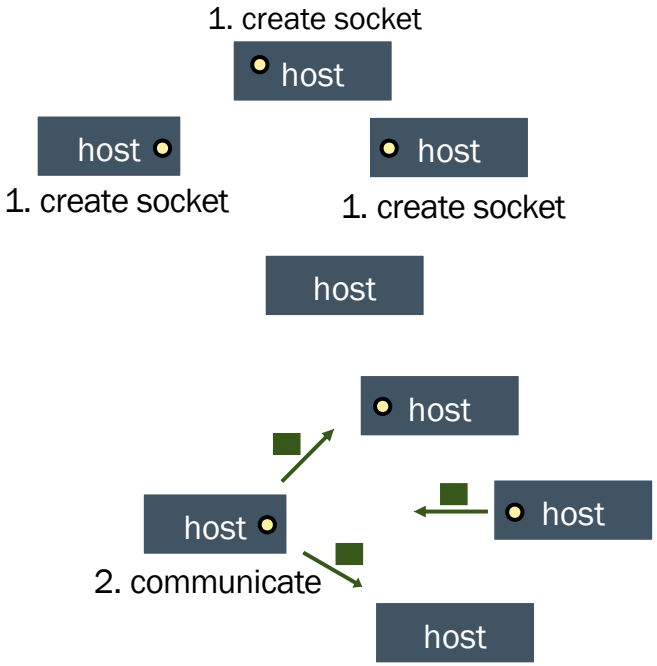
- Used less frequently than stream sockets
  - they provide no flow control, ordering, or reliability
  - really, provides best effort communication
- Often used as a building block
  - streaming media applications
  - sometimes, DNS lookups



Note: this is also called "*connectionless*" communication

TCP connections

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- Clients and servers communicate by sending streams of bytes over *connections*. Each connection is:
  - point-to-point: connects a pair of processes
  - full-duplex: data can flow in both directions at the same time
  - reliable: data send/receive order is preserved
- A socket is an endpoint of a connection
  - socket address is: IPAddress:port pair
- A port is a 16-bit integer that identifies a process:
  - ephemeral port: assigned automatically by the client kernel when client makes a connection
  - well-known port: associated with some service provided by a server:

  (e.g. 80 is HTTP/Web)

Network Ports

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- Every computer has a numbered set of locations that represent the available "services" can be reached at
  - Ports are numbered 0 to 65535 → 16 bits
    - 0 to 1023 are called "well known" or "reserved" ports, where you need special (root) privileges to receive on these ports
  - Each transport (UDP/TCP) has its own list of ports
- Interesting port numbers
  - 20/21 - file transfer protocol (file passing)
  - 22 - secure shell (remote access)
  - 25 - Simple mail transfer protocol (email)
  - 53 - domain name service (internet naming)
  - 80 - HTTP (web)

Anatomy of a connection

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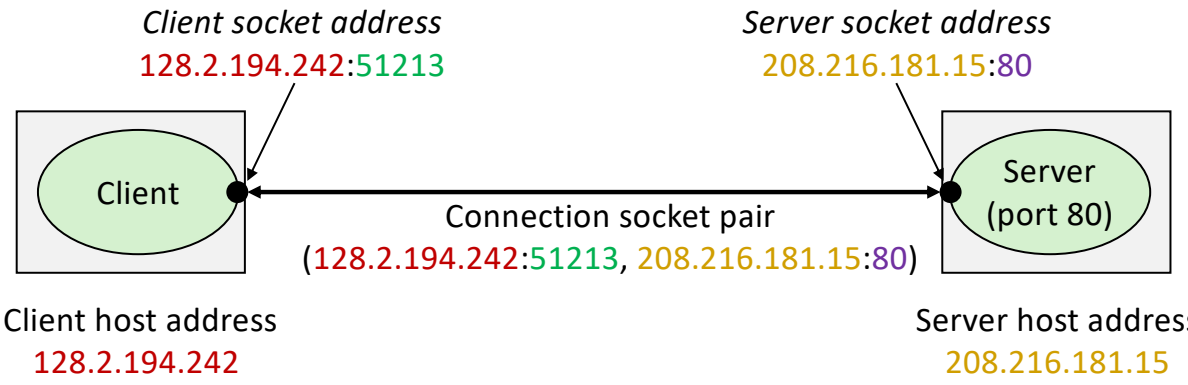
- A connection is uniquely identified by the socket addresses of its endpoints (*socket pair*)
  - **`(client IP:client port, server IP:server port)`**



Programming a client

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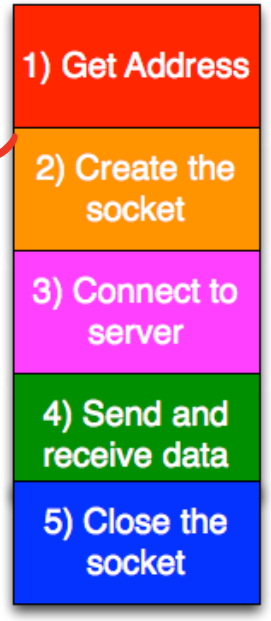
- We'll start by looking at the API from the point of view of a client connecting to a server over TCP
  - there are five steps:
    - figure out the address/port to connect to
    - create a socket
    - connect the socket to the remote server
    - `read()` and `write()` data using the socket
    - close the socket

1) get address
2) Create socket
3) connection
4) read/write
5) close



inet_aton()

1) Get Address

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- The `inet_aton()` converts a IPv4 address into the UNIX structure used for processing:

```
int inet_aton(const char *addr, struct in_addr *inp);
```

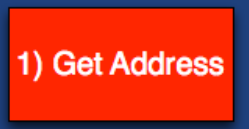
- Where,
  - `addr` is a string containing the address to use (e.g., "166.84.7.99")
  - `inp` is a pointer to the structure containing the UNIX internal representation of an address, used in later network communication calls

An example:

1. IPV4 to Binary: 166.84.7.99 → 10100110 01010100 00000111 01100011 (2790524771)
2. Little Endian→Big Endian:01100011 00000111 01010100 10100110
3. Binary → Decimal: 1661424806

`inet_aton()` returns 0 if failure!

Putting it to use ...



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```c
#include <stdlib.h>
#include <arpa/inet.h>

int main(int argc, char **argv) {
  struct sockaddr_in v4, sa; // IPv4
  struct sockaddr_in6 sa6; // IPv6

  // IPv4 string to sockaddr_in. (both ways)
  inet_aton("192.0.1.1", &(v4.sin_addr));
  inet_pton(AF_INET, "192.0.2.1", &(sa.sin_addr));

  // IPv6 string to sockaddr_in6.
  inet_pton(AF_INET6, "2001:db8:63b3:1::3490", &(sa6.sin6_addr));

  return( 0 );
}
```

IPV4

IPV6

Getting back to strings?

1) Get Address

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- The `inet_ntoa()` converts a UNIX structure for an IPv4 address into an ASCII string:

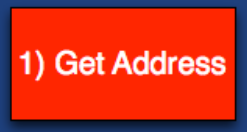
```
char *inet_ntoa(struct in_addr in);
```

```
struct sockaddr_in caddr, sa; // IPv4
struct sockaddr_in6 sa6; // IPv6
char astring[INET6_ADDRSTRLEN];  // IPv6

// Start by converting
inet_aton( "192.168.8.9", &caddr.sin_addr);
inet_pton(AF_INET, "192.0.2.1", &(sa.sin_addr));
inet_pton(AF_INET6, "2001:db8:63b3:1::3490", &(sa6.sin6_addr));

// Return to ASCII strings
inet_ntop(AF_INET6, &(sa6.sin6_addr), astring, INET6_ADDRSTRLEN);
printf( "IPv4 : %s\n", inet_ntoa(caddr.sin_addr) );
printf( "IPv6 : %s\n", astring );
```

Domain Name Service (DNS)



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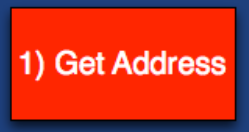
- People tend to use DNS names, not IP addresses
  - the sockets API lets you convert between the two
  - it's a complicated process, though:
    - a given DNS name can have many IP addresses
    - many different DNS names can map to the same IP address
      - an IP address will map onto at most one DNS names, and maybe none
    - a DNS lookup may require interacting with many DNS servers

Note: The "dig" Linux program is used to check DNS entries.

Domain Name Service (DNS)



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- People
  - the soc
  - it's a c
    - a
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    - a

```
$ dig lion.cse.psu.edu

; <<>> DiG 9.9.2-P1 <<>> lion.cse.psu.edu
;; global options: +cmd
;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 53447
;; flags: qr rd ra; QUERY: 1, ANSWER: 1, AUTHORITY: 0, ADDITIONAL: 1

;; OPT PSEUDOSECTION:
; EDNS: version: 0, flags:; MBZ: 0005 , udp: 4000
;; QUESTION SECTION:
;lion.cse.psu.edu.              IN      A

;; ANSWER SECTION:
lion.cse.psu.edu.       5       IN      A       130.203.22.184

;; Query time: 38 msec
;; SERVER: 127.0.1.1#53(127.0.1.1)
;; WHEN: Tue Nov 12 14:02:11 2013
;; MSG SIZE  rcvd: 61
```

Note: The "dig" Linux program is used to check DNS entries.

The FQDN

1) Get Address

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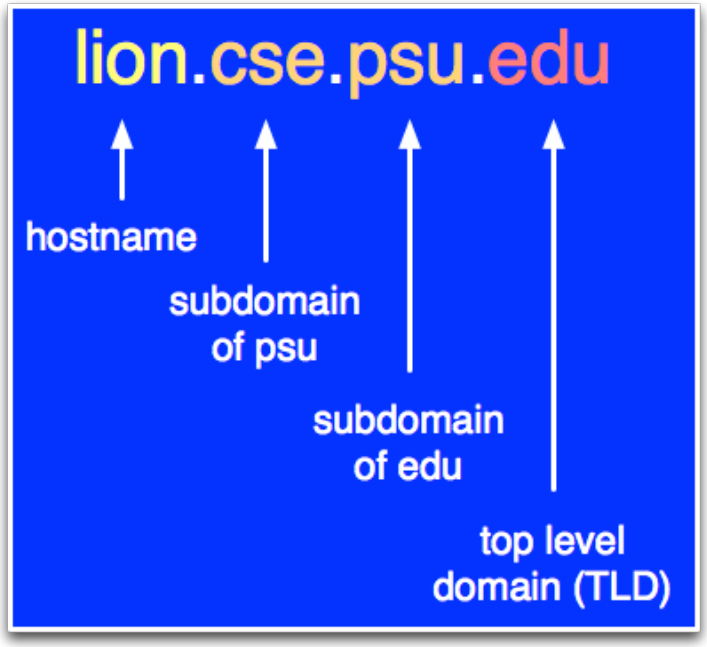
- Every system that is supported by DNS has a unique fully qualified domain name

(FQDN)



DNS hierarchy

1) Get Address

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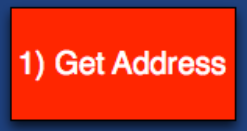
Resolving DNS names



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- The POSIX way is to use `getaddrinfo()` – complicate way
- a pretty complicated system call; the basic idea…
  - set up a "hints" structure with constraints you want respected
    - e.g., IPv6, IPv4, or either
  - indicate which host and port you want resolved
    - host: a string representation; DNS name or IP address
  - returns a list of results packet in an "`addrinfo`" struct
  - free the `addrinfo` structure using `freeaddrinfo()`

DNS resolution (the easy way)

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1) Get Address

- The `gethostbyname()` uses DNS to look up a name and return the host information

```
struct hostent *gethostbyname(const char *name);
```

↘ DNS

- Where,
  - `name` is a string containing the host/domain name to find
  - `hostent` is a structure with the given host name. Here name is either a hostname, or an IPv4 address in standard dot notation. The structure includes:
    - `hostent->h_name` (fully qualified domain name [redacted]) FQDN
    - `hostent->h_addr_list` (list of pointers to IP addresses)

DNS resolution (the eas 1) Get Address y)

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- The `gethostbyname()` uses DNS to look up a name and return the host information

```
struct hostent *gethostbyname(const char *name);
```

- Where,
  - `name` is
  - `hosten` hostname, or an IPv
    - `host`
    - `host`

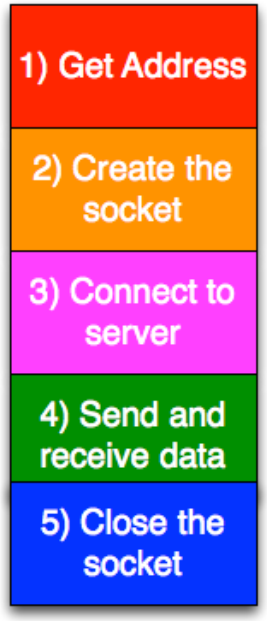
```
char *hn = "lion.cse.psu.edu";
struct hostent * hstinfo;
struct in_addr **addr_list;
if ((hstinfo = gethostbyname(hn)) == NULL) {
  return -1;
}

addr_list = (struct in_addr **)hstinfo->h_addr_list;
printf( "DNS lookup [%s] address [%s]\n", hstinfo->h_name,
        inet_ntoa(*addr_list[0]) );
```

```
$ ./network
DNS lookup [lion.cse.psu.edu] address [130.203.22.184]
$
```

Programming a client

- We'll start by looking at the API from the point of view of a client connecting to a server over TCP
  - there are five steps:
    - figure out the address/port to connect to
    - create a socket
    - connect the socket to the remote server
    - read() and write() data using the socket
    - close the socket



Creating a socket

2) Create the socket

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- The `socket()` function creates a file handle for use in communication:

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

- Where,
  - `domain` is the communication domain
    - `AF_INET` (IPv4), `AF_INET6` (IPv6)
  - `type` is the communication semantics (stream vs. datagram)
    - SOCK_STREAM is stream (using TCP by default)
    - SOCK_DGRAM is datagram (using UDP by default)
  - `protocol` selects a protocol from available (not used often)

Note: creating a socket doesn't connect to anything

Creating a socket

2) Create the socket

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- The `socket()` function creates a file handle for use in communication:

```
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```

- Where,
  - `domai`
    - AF_
  - `type` i
    - SOC
    - SOCK_DGRAM is datagram (using UDP by default)
  - `protocol` selects a protocol from available (not used often)

```
// Create the socket
int sockfd;
sockfd = socket(AF_INET, SOCK_STREAM, 0);
if (sockfd == -1) {
    printf( "Error on socket creation [%s]\n", strerror(errno) );
    return( -1 );
}
```

Note: creating a socket doesn't connect to anything

Specifying an address

3) Connect to server

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- The next step is to create an address to connect to by specifying the address and port in the proper form.
  - protocol family (`addr.sin_family`)
  - port (`addr.sin_port`)
  - IP address (`addr.sin_addr`)

```
// Variables
char *ip = "127.0.0.1";
unsigned short port = 16453;
struct sockaddr_in caddr;

// Setup the address information
caddr.sin_family = AF_INET;
caddr.sin_port = htons(port);
if ( inet_aton(ip, &caddr.sin_addr) == 0 ) {
  return( -1 );
}
```

Network byte order

3) Connect to server

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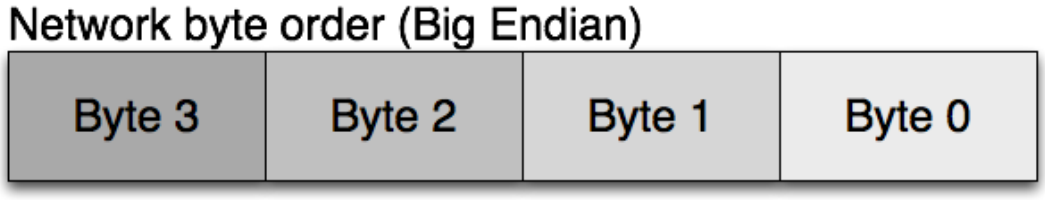
- When sending data over a network you need to convert your integers to be in network byte order, and back to host byte order upon receive:

```
uint64_t htonll64(uint64_t hostlong64);
uint32_t htonl(uint32_t hostlong);
uint16_t htons(uint16_t hostshort);
uint64_t ntohll64(uint64_t hostlong64);
uint32_t ntohl(uint32_t netlong);
uint16_t ntohs(uint16_t netshort);
```

- Where each of these functions receives a NBO or HBO 64/ 32 /16 byte and converts it to the other.



connect()

3) Connect to server

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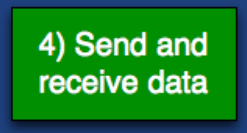
- The connect() system call connects the socket file descriptor to the specified address

```
int connect(int sockfd, const struct sockaddr *addr,
                        socklen_t addrlen);
```

- Where,
  - sockfd is the socket (file handle) obtained previously
  - addr - is the address structure
  - addlen - is the size of the address structure
  - Returns 0 if successfully connected, -1 if not

```
if ( connect(sockfd, (const struct sockaddr *)&caddr,
             sizeof(caddr)) == -1 ) {
  return( -1 );
}
```

Reading and Writing



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- Primitive reading and writing only process only blocks of opaque data:

```
ssize_t write(int fd, const void *buf, size_t count);
   ssize_t read(int fd, void *buf, size_t count);
```

- Where `fd` is the file descriptor, `buf` is an array of bytes to write from or read into, and `count` is the number of bytes to read or write
- The value returned is the number by both is bytes read or written.
  - Be sure to always check the result
- On reads, you are responsible for supplying a buffer that is large enough to put the output into.
  - look out for memory corruption when buffer is too small …

close()

5) Close the socket

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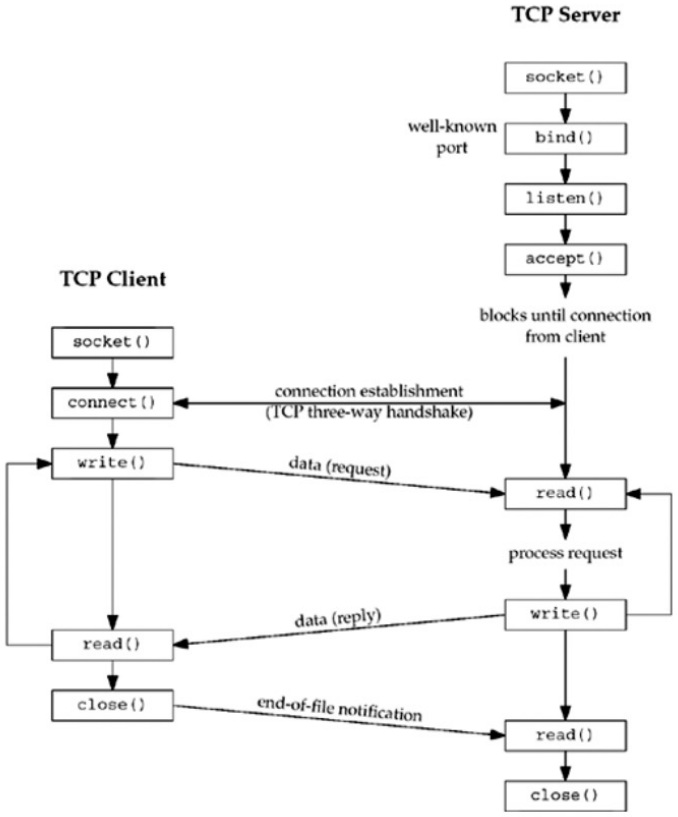
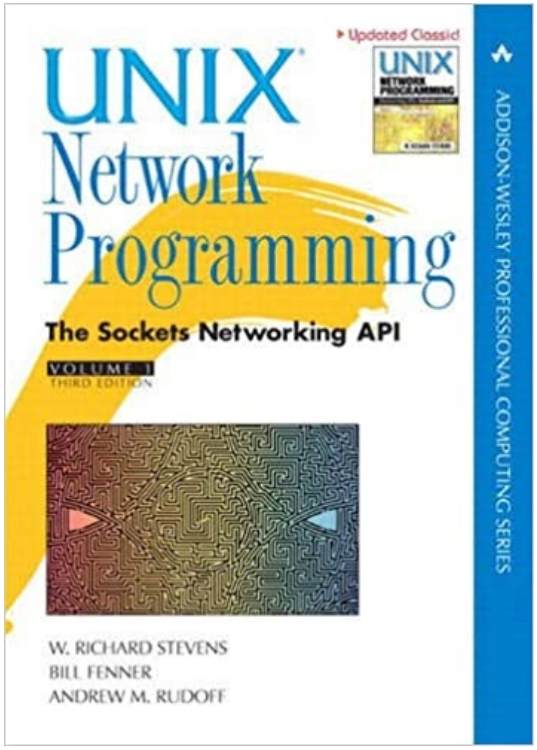
- `close()` closes the connection and deletes the associated entry in the operating system's internal structures

```
close( socket_fd );
socket_fd = -1;
```

Note: set handles to –1 to avoid use after close.

Elementary TCP client/server





Programming a server

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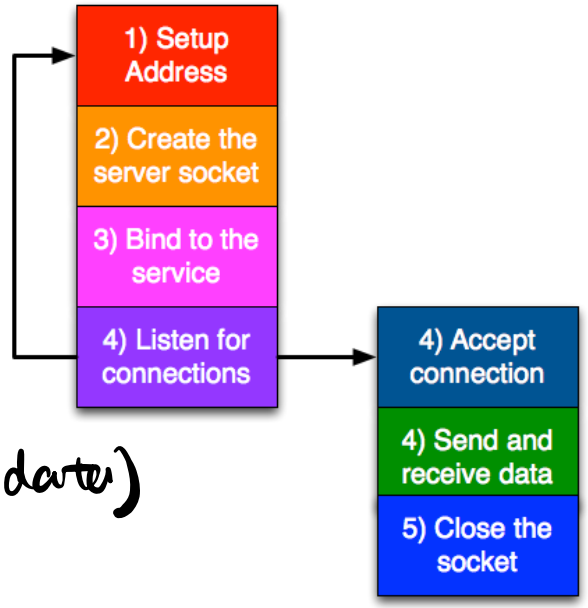
- Now we'll look at the API from the point of view of a server who receives connections from clients
  - there are seven steps:
    - figure out the port to "bind" to
    - create a socket
    - bind the service
    - begin listening for connections
    - receive connection
    - read() and write() data (send or receive data)
    - close the socket

server connection



Setting up a server address

1) Setup Address

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- All you need to do is specify the service port you will use for the connection:

```
struct sockaddr_in saddr;
saddr.sin_family = AF_INET;
saddr.sin_port = htons(16453);
saddr.sin_addr.s_addr = htonl(INADDR_ANY);
```

- However, you don't specify an IP address because you are receiving connections at the local host.
  - Instead you use the special "any" address

`htonl(INADDR_ANY)`

Next: creating the socket is as with the client

2) Create the server socket

int socket(domain, type, protocol)

IPV4/IPV6 SOCK_STREAM

sock_DGRAM

Binding the service

3) Bind to the service

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- The bind() system call associates a socket with the server connection (e.g., taking control of HTTP)

```
int bind(int sockfd, const struct sockaddr *addr, socklen_t *addrlen)
```

- Where,
  - `sockfd` is the socket (file handle) obtained previously
  - `addr` - is the address structure
  - `addlen` - is the size of the address structure
  - Returns 0 if successfully connected, -1 if not

↓ similar to connect() in client side.

```
if ( bind(sock, (const struct sockaddr *)&saddr,
          sizeof(saddr)) == -1 ) {
  return( -1 );
}
```

Listening for connections

4) Listen for connections

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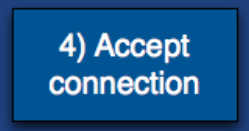
- The listen() system call tells the OS to receive connections for the process

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

- Where,
  - `sockfd` is the socket (file handle) obtained previously
  - `backlog` - is the number of connections to queue
    - A program may process connections as fast as it wants, and the OS will hold the client in a waiting state until you are ready
    - Beware of waiting too long (timeout)

```
if ( listen(sock, 5) == -1 ) {
  return( -1 );
}
```

Accepting connections



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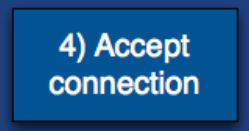
- The `accept()` system call receives the connection from the client:

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

- Where,
  - `sockfd` is the socket (file handle) obtained previously
  - `addr` - is the address structure for client (filled in)
  - `addlen` - is the size of the address structure
  - Returns the new socket handle or -1 if failure

bind( )
listen( )
accept( )

Accepting connections



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  - `addlen` - is the size of the address structure
  - Returns the new socket handle or -1 if failure

```
inet_len = sizeof(caddr);
if ( (client = accept(server, (struct sockaddr *)&caddr, inet_len )) == -1 )
{
  printf( "Error on client accept [%s]\n", strerror(errno) );
  close(server);
  return( -1 );
}
printf( "Server new client connection [%s/%d]",
        inet_ntoa(caddr.sin_addr), caddr.sin_port );
```

The rest ...

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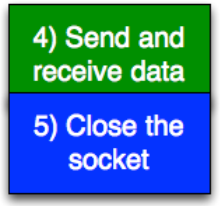
- From the server perspective, receiving and sending on the newly received socket is the same as if it were a client
  - `read()` and `write()` for sending and receiving
  - `close()` for closing the socket



Putting it all together (client)

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```c
int client_operation( void ) {

    int socket_fd;
    uint32_t value;
    struct sockaddr_in caddr;
    char *ip = "127.0.0.1";

    caddr.sin_family = AF_INET;
    caddr.sin_port = htons(16453);
    if ( inet_aton(ip, &caddr.sin_addr) == 0 ) {
        return( -1 );
    }

    socket_fd = socket(PF_INET, SOCK_STREAM, 0);
    if (socket_fd == -1) {
        printf( "Error on socket creation [%s]\n", strerror(errno) );
        return( -1 );
    }

    if ( connect(socket_fd, (const struct sockaddr *)&caddr, sizeof(caddr)) == -1 ) {
        printf( "Error on socket connect [%s]\n", strerror(errno) );
        return( -1 );
    }

    value = htonl( 1 );
    if ( write( socket_fd, &value, sizeof(value)) != sizeof(value) ) {
        printf( "Error writing network data [%s]\n", strerror(errno) );
        return( -1 );
    }
    printf( "Sent a value of [%d]\n", ntohl(value) );

    if ( read( socket_fd, &value, sizeof(value)) != sizeof(value) ) {
        printf( "Error reading network data [%s]\n", strerror(errno) );
        return( -1 );
    }
    value = ntohl(value);
    printf( "Receivd a value of [%d]\n", value );

    close(socket_fd); // Close the socket
    return( 0 );
}
```

Putting it all together (server)

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```c
int server_operation( void ) {

    int server, client;
    uint32_t value, inet_len;
    struct sockaddr_in saddr, caddr;

    saddr.sin_family = AF_INET;
    saddr.sin_port = htons(16453);
    saddr.sin_addr.s_addr = htonl(INADDR_ANY);

    server = socket(PF_INET, SOCK_STREAM, 0);
    if (server == -1) {
        printf( "Error on socket creation [%s]\n", strerror(errno) );
        return( -1 );
    }

    if ( bind(server, (struct sockaddr *)&saddr, sizeof(saddr)) == -1 ) {
        printf( "Error on socket bind [%s]\n", strerror(errno) );
        return( -1 );
    }

    if ( listen( server, 5 ) == -1 ) {
        printf( "Error on socket listen [%s]\n", strerror(errno) );
        return( -1 );
    }
```

… Together (server, part 2)

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```
    while ( 1 ) {
        inet_len = sizeof(caddr);
        if ( (client = accept( server, (struct sockaddr *)&caddr, &inet_len )) == -1 ) {
            printf( "Error on client accept [%s]\n", strerror(errno) );
            close(server);
            return( -1 );
        }
        printf( "Server new client connection [%s/%d]", inet_ntoa(caddr.sin_addr), caddr.sin_port );
        if ( read( client, &value, sizeof(value)) != sizeof(value) ) {
            printf( "Error writing network data [%s]\n", strerror(errno) );
            close(server);
            return( -1 );
        }
        value = ntohl(value);
        printf( "Receivd a value of [%d]\n", value );
        value++;
        value = htonl(value);
        if ( write( client, &value, sizeof(value)) != sizeof(value) ) {
            printf( "Error writing network data [%s]\n", strerror(errno) );
            close(server);
            return( -1 );
        }
        printf( "Sent a value of [%d]\n", value );
        close(client); // Close the socket
    }
    return( 0 );
}
```