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CMPSC 311 - Introduction to Systems Programming

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Network Programming

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Professors:

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

If you ask if I got a UDP
joke



is
it still a UDP joke?

What is a network?



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- A network is a collection of computing devices that share a transmission media

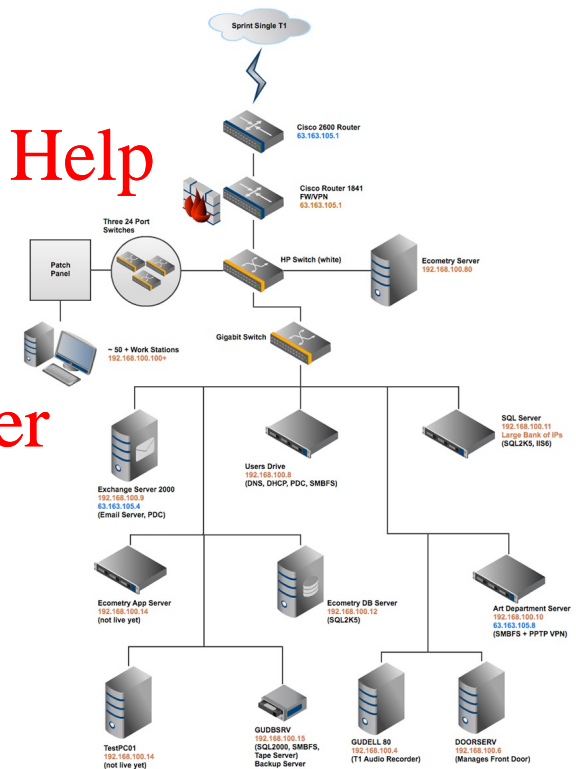
- Traditional wired networks (ethernet)
- High-speed backbone (fibre)
- Wireless (radio)
- Microwave
- Infrared

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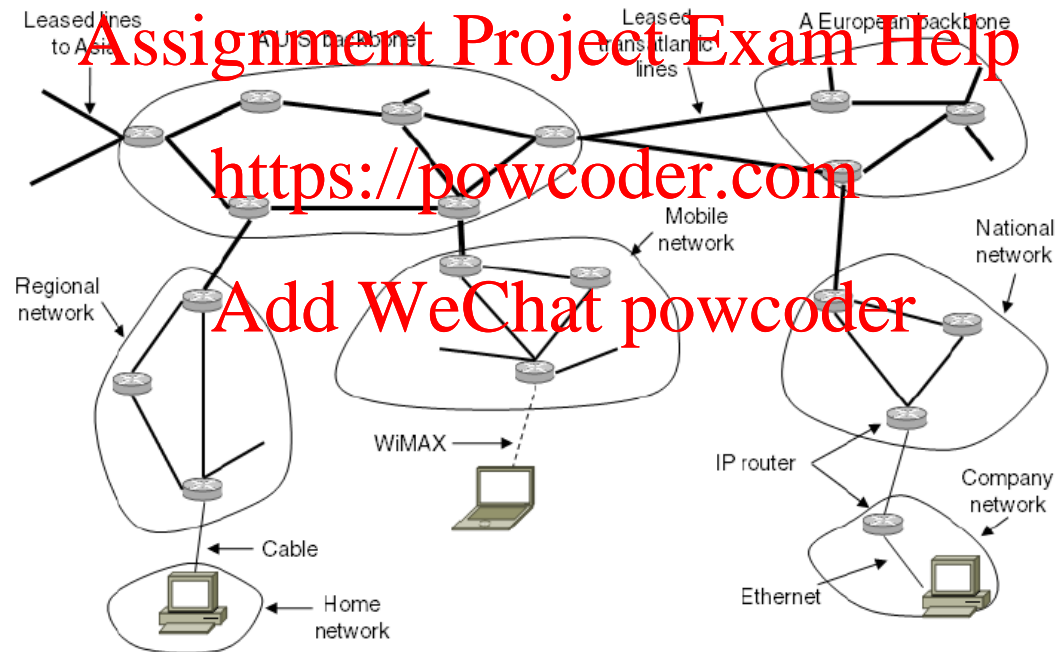
- The way the network is organized is called the **network topology**



The Internet



The Internet is an interconnected collection of many networks.



Internet protocol stack (TCP/IP)



- **application**: supporting network applications

- FTP, SMTP, HTTP, DNS

- **transport**: process-process data transfer

- TCP, UDP

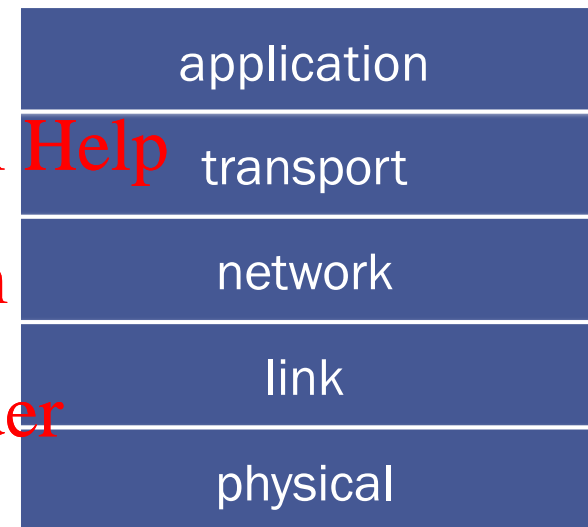
- **network**: routing of datagrams from source to destination

- IP, routing protocols

- **link**: data transfer between neighboring network elements

- PPP, Ethernet

- **physical**: bits “on the wire”



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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).

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Networks Systems



- 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](https://powcoder.com) or just protocol

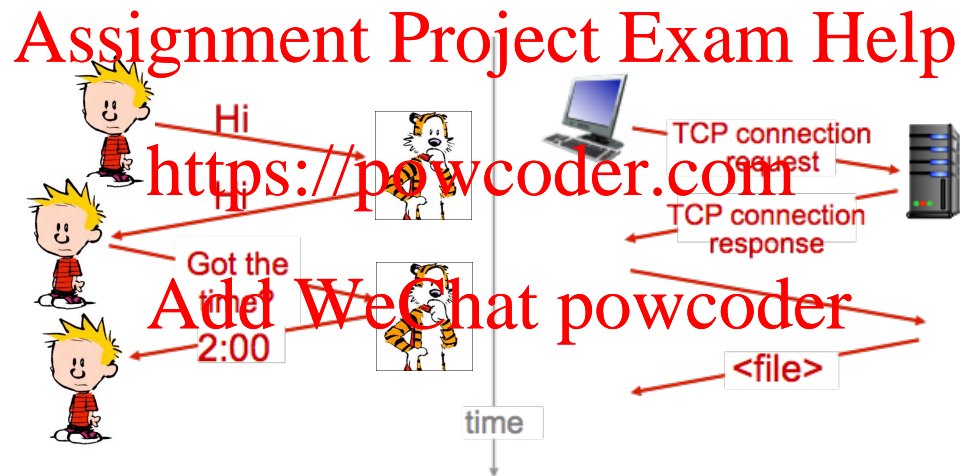
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What's a Protocol?



- 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

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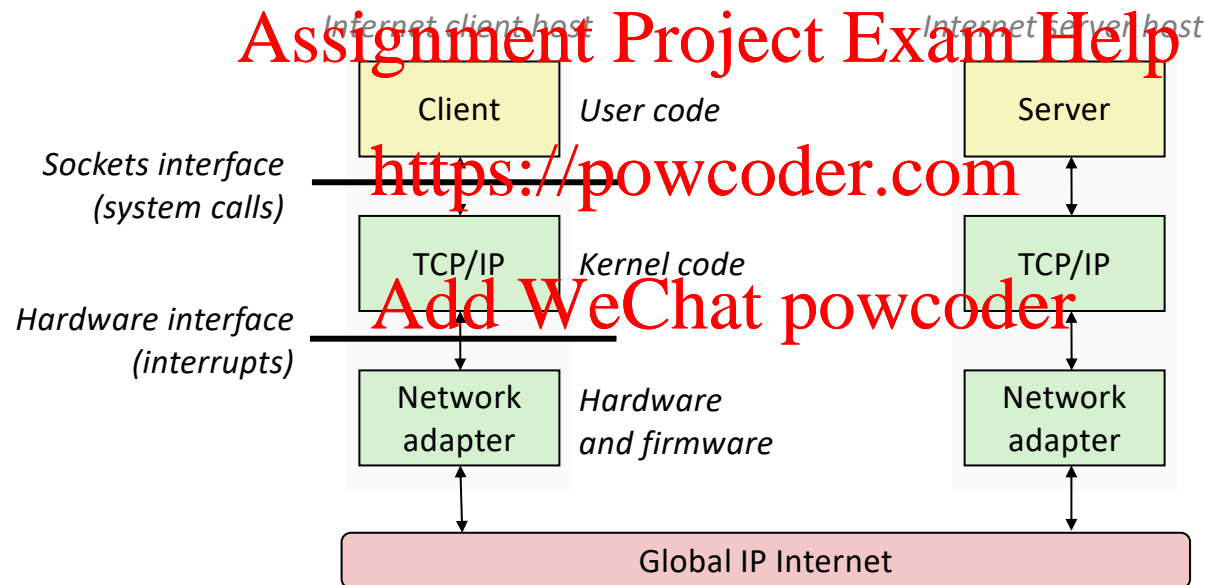
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Hardware and Software Organization of Internet Application



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

IP addresses



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- 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

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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

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Networks and sockets



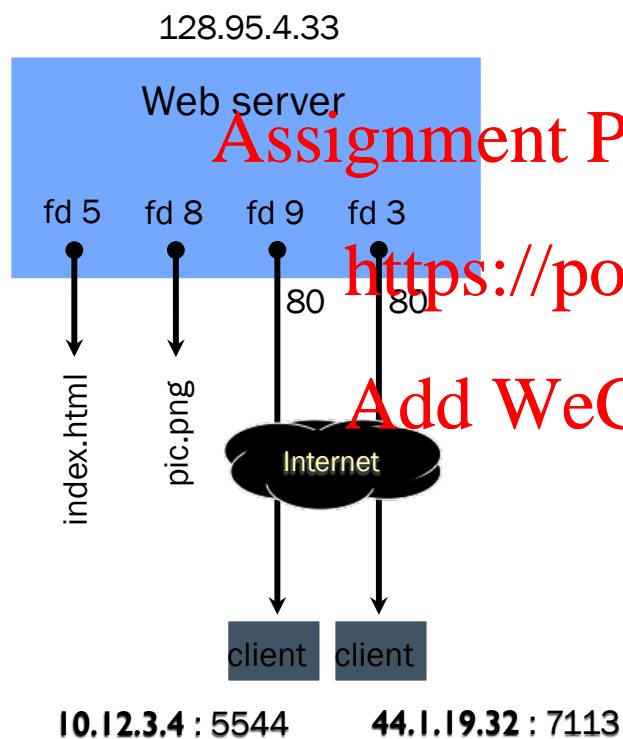
- UNIX makes all I/O look like file I/O
 - the good news is that you can use `read()` and `write()` to interact with remote computers over a network.
 - just like with files....
 - A program can have multiple network channels open at once
 - you need to pass `read()` and `write()` a file descriptor to 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



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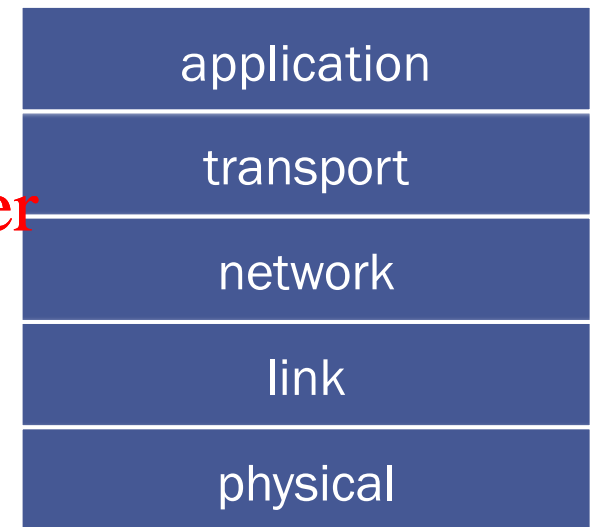
file descriptor	type	connected to?
0	pipe	stdin (console)
1	pipe	stdout (console)
2	pipe	stderr (console)
3	TCP socket	local: 128.95.4.33:80 remote: 44.1.19.32:7113
5	file	index.html
8	file	pic.png
9	TCP socket	local: 128.95.4.33:80 remote: 10.12.3.4:5544

OS's descriptor table

Types of sockets



- 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)



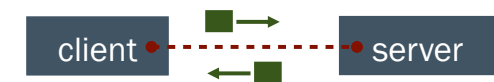
Stream (TCP) sockets



- 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



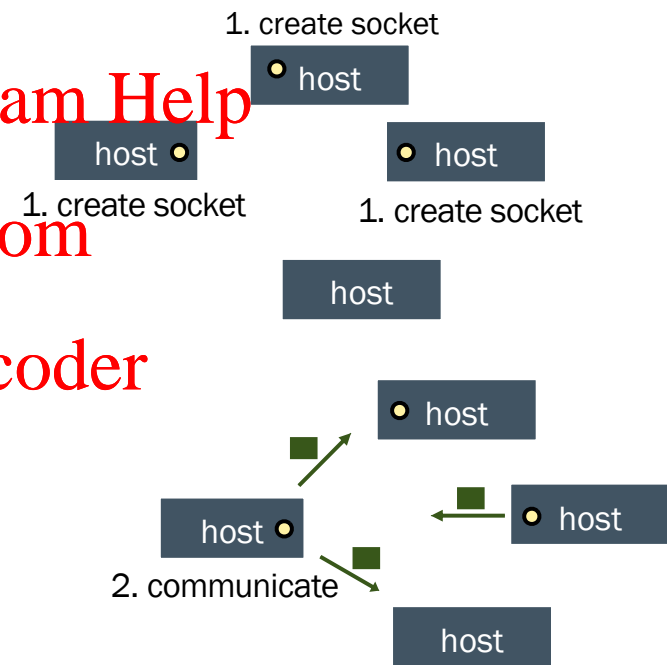
3. close connection

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: IP address/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
 - 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



- A connection is uniquely identified by the socket addresses of its endpoints (*socket pair*)

- (client IP:client port, server IP:server port)



51213 is an ephemeral port
allocated by the kernel

80 is a well-known port
associated with Web servers

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

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1) Get Address

2) Create the socket

3) Connect to server

4) Send and receive data

5) Close the socket

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:

- IPv4 to Binary: 166.84.7.99 → 10100110 01010100 00000111 01100011
(2790524771)
- Little Endian → Big Endian: 01100011 00000111 01010100 10100110
- Binary → Decimal: 1661424806

`inet_aton()` returns 0 if failure!

Putting it to use ...

1) Get Address



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```
#include <stdio.h>
#include <arpa/inet.h>

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

    // IPv4 string to sockaddr_in. (both ways)
    inet_aton("192.0.2.1", &(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 );
}
```

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)

1) Get Address



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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)

1) Get Address



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```
$ 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

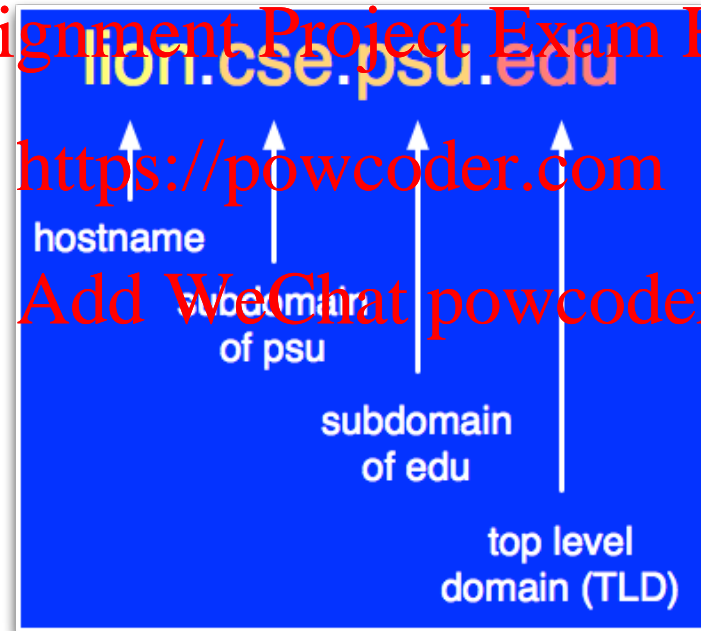
1) Get Address



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

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DNS hierarchy

1) Get Address



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Resolving DNS names

1) Get Address



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- The POSIX way is to use `getaddrinfo()`
- 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()`

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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);
```

- 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 FDQN)
 - ▶ `hostent->h_addr_list` (list of pointers to IP addresses)

DNS resolution (the easy way)

1) Get Address



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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

- ▶ `hostent`

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]
$
```

hostname,

Programming a client



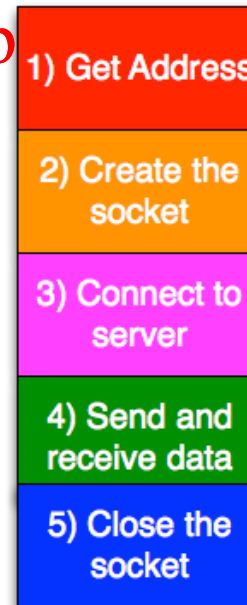
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- We'll start by looking at the API from the point of view of a client connecting to a server over TCP
 - there are five steps:
 - figure out the address/port to connect to
 - create a socket
 - connect the socket to the remote server
 - read() and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

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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:

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

- Where,

- ▶ `domain`

- ▶ `AF_INET`

- ▶ `type`

- ▶ `SOCK_STREAM`

- ▶ `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`)

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```
// 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 );
}
```

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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:

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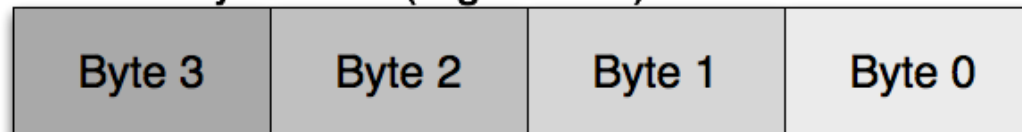
```
uint64_t htonl64(uint64_t hostlong64);  
uint32_t htonl(uint32_t hostlong);  
uint16_t htons(uint16_t hostshort);  
uint64_t htonl64(uint64_t hostlong64);  
uint32_t ntohl(uint32_t netlong);  
uint16_t ntohs(uint16_t netshort);
```

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

Network byte order (Big Endian)



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

4) Send and
receive data



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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 of 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

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```
close( sockfd );
```

```
socket_fd = -1;
```

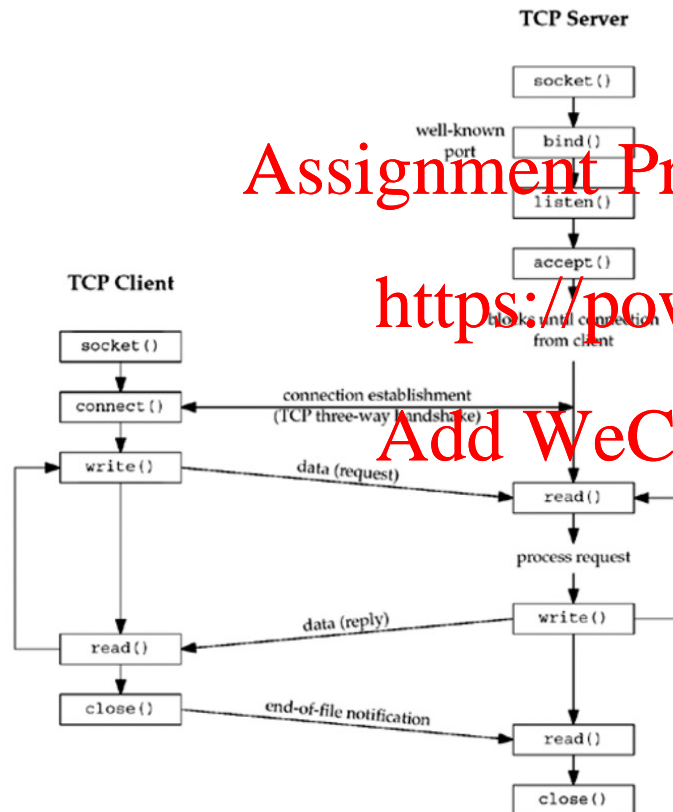
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Note: set handles to `-1` to avoid use after close.

Elementary TCP client/server



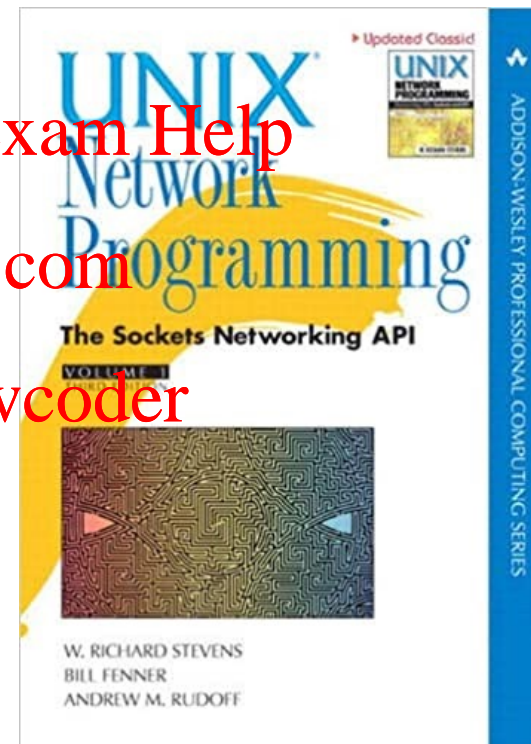
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Programming a server

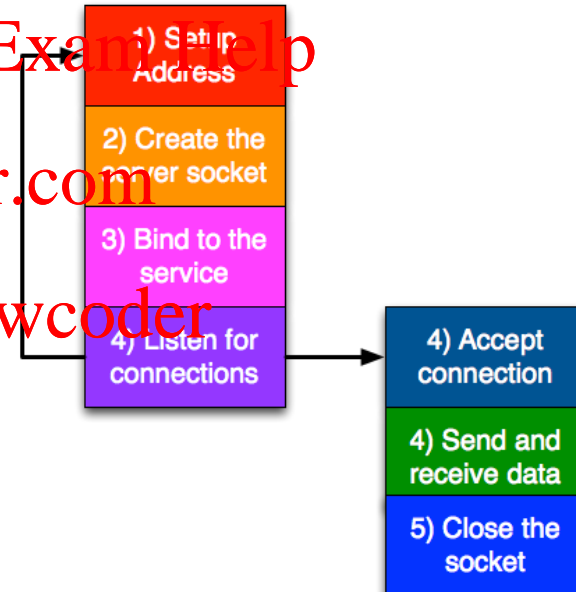


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- Now we'll look at the API from the point of view of a server who receives connections from clients

- 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
- close the socket



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:

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```
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

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
- `addrlen` - is the size of the address structure
- Returns 0 if successfully connected, -1 if not

```
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

4) Accept connection



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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)
- `addrlen` - is the size of the address structure

- Returns the new socket handle or -1 if failure

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Accepting connections

4) Accept connection



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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,

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- `sockfd` is the socket (file handle) obtained previously
- `addr` - is the address structure for client (filled in)
- `addrlen` - is the size of the address structure

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- Returns the new socket and error if failure

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```
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 ...

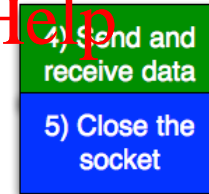


- From the server perspective, receiving and sending on the newly received socket is the same as if it were a client
 - `read()` and `write()` for sending and receiving
 - `close()` for closing the socket

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Putting it all together (client)



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```
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( 6555 );  
    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( "Received a value of [%d]\n", value );  
  
    close(socket_fd); // Close the socket  
    return( 0 );  
}
```

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Putting it all together (server)



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```
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( "Received 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 );
}
```