Network Programming: Part I

15-213: Introduction to Computer Systems
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A Client-Server Transaction

Most network applications are based on the client-server model:

- A server process and one or more client processes
- Server manages some resource
- Server provides service by manipulating resource for clients
- Server activated by request from client (vending machine analogy)

Note: clients and servers are processes running on hosts (can be the same or different hosts)
Computer Networks

- **A network** is a hierarchical system of boxes and wires organized by geographical proximity
  - LAN (Local Area Network) spans a building or campus
    - Ethernet is most prominent example
  - WAN (Wide Area Network) spans country or world
    - Typically high-speed fiber optics

- An **internetwork (internet)** is an interconnected set of networks
  - The Global IP Internet (uppercase “I”) is the most famous example of an internet (lowercase “i”)

- Let’s see how an internet is built from the ground up
Hardware Organization of a Network Host

- **CPU chip**
  - register file
  - ALU

- **MI**

- **I/O bridge**

- **Main memory**

- **System bus**

- **Memory bus**

- **Expansion slots**

- **I/O bus**

- **USB controller**
  - mouse
  - keyboard

- **Graphics adapter**
  - monitor

- **Disk controller**
  - disk

- **Network adapter**
  - network

**Additional components:**
- **Network adapter**
- **Graphics adapter**
- **Disk controller**
- **I/O bus**
- **Expansion slots**
Lowest Level: Ethernet Segment

- Ethernet segment consists of a collection of *hosts* connected by wires (twisted pairs) to a *switch*
- Spans room or floor in a building
- **Operation**
  - Each Ethernet adapter has a unique 48-bit address (*MAC address*)
    - E.g., 00:16:ea:e3:54:e6
  - Hosts send bits to any other host in chunks called *frames*
  - Switch cleverly learns which hosts are reachable from which ports and selectively copies frames from source to destination
Next Level: Bridged Ethernet Segment

- Spans building or campus
- Specialized computers called *routers* link network segments
Conceptual View of LANs

For simplicity, LANs are often shown as a collection of hosts attached to a single wire:
Next Level: internets

- Routers also connect multiple incompatible LANs
- The connected networks are called an internet (lower case)

LAN 1 and LAN 2 might be completely different, totally incompatible (e.g., Ethernet, Fiber Channel, 802.11*, T1-links, DSL, ...)
Ad hoc interconnection of networks

- No particular topology
- Vastly different router & link capacities

Send packets from source to destination by hopping through networks

- Router forms bridge from one network to another
- Different packets may take different routes
The Notion of an Internet Protocol

- How is it possible to send bits across incompatible LANs and WANs?

- Solution: agree on operating *protocols* and implement them in router/host software
  - Protocol is a set of rules that governs how hosts and routers should cooperate when they transfer data from network to network.
What Does an internet Protocol Do?

- Provides a *naming scheme*
  - An internet protocol defines a uniform format for *host addresses*
  - Each host (and router) is assigned at least one of these internet addresses that uniquely identifies it

- Provides a *delivery mechanism*
  - An internet protocol defines a standard transfer unit (*packet*)
  - Packet consists of *header* and *payload*
    - Header: contains info such as packet size, source and destination addresses
    - Payload: contains data bits sent from source host
    - The payload might be another packet (and a frame’s payload is usually a packet!).
Transferring internet Data Via Encapsulation

LAN1

1. data

internet packet

LAN1 frame

2. data, PH, FH1

Host A

client

protocol software

LAN1 adapter

Host B

server

protocol software

LAN2 adapter

Router

3. data, PH, FH1

4. data, PH, FH2

5. data, PH, FH2

6. data, PH, FH2

7. data, PH, FH1

8. data

PH: Internet packet header

FH: LAN frame header
Other Issues

- We are glossing over a number of important questions:
  - What if different networks have different maximum frame sizes? (segmentation)
  - How do routers know where to forward frames?
  - How are routers informed when the network topology changes?
  - What if packets get lost?

- These (and other) questions are addressed by the area of systems known as *computer networking*
Global IP Internet (upper case)

- Most famous example of an internet

- Based on the TCP/IP protocol family
  - IP (Internet Protocol):
    - Provides *basic naming scheme* and unreliable *delivery capability* of packets (datagrams) from *host-to-host*
  - UDP (Unreliable Datagram Protocol):
    - Uses IP to provide *unreliable* datagram delivery from *process-to-process*
  - TCP (Transmission Control Protocol):
    - Uses IP to provide *reliable* byte streams from *process-to-process* over *connections*

- Accessed via a mix of Unix file I/O and functions from the *sockets interface*
Hardware and Software Organization of an Internet Application

**Internet client host**

- **Client**: User code
- **TCP/IP**: Kernel code
- **Network adapter**: Hardware and firmware

**Internet server host**

- **Server**: User code
- **TCP/IP**: Kernel code
- **Network adapter**: Hardware and firmware

**Global IP Internet**

**Sockets interface** (system calls)

**Hardware interface** (interruptions)
A Programmer’s View of the Internet

1. Hosts are mapped to a set of 32-bit IP addresses
   - 128.2.203.179

2. A process on one Internet host can communicate with a process on another Internet host over a connection
Oops: IPv4 and IPv6

- The original Internet Protocol, with its 32-bit addresses, is known as Internet Protocol Version 4 (IPv4)
- 1996: Internet Engineering Task Force (IETF) introduced Internet Protocol Version 6 (IPv6) with 128-bit addresses
  - Intended as the successor to IPv4
- Majority of Internet traffic still carried by IPv4
  - But IPv6 is finally taking hold
  - % of users access Google services using IPv6:
    - Nov. 2014: 4%
    - Nov. 2015: 7%
    - Nov. 2016: 14%
- We will focus on IPv4, but the IPv6 API is similar.
IPv4: Dotted Decimal Notation

- By convention, each byte in a 32-bit IP address is represented by its decimal value and separated by a period
  - IP address: \(0x8002C2F2 = 128.2.194.242\)

- Caveat emptor: IP addresses are transmitted in big endian!
Internet Connections

- 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*: stream of bytes sent by the source is eventually received by the destination in the same order it was sent.

- A **socket** is an endpoint of a connection
  - *Socket address* is an **IP address:port** pair

- A **port** is a 16-bit integer that identifies a process:
  - *Ephemeral port*: Assigned automatically by client kernel when client makes a connection request.
  - *Well-known port*: Associated with some **service** provided by a server (e.g., port 80 is associated with Web servers)
Well-known Ports and Service Names

- Popular services have permanently assigned *well-known ports and corresponding well-known service names*:
  - echo server: 7/echo
  - ssh servers: 22/ssh
  - email server: 25/smtp
  - Web servers: 80/http
  - Secure Web servers: 443/https

- Mappings between well-known ports and service names is contained in the file `/etc/services` on each Linux machine.

- On Linux, only the root user (administrator) is allowed to bind to ports below 1024!
Anatomy of a Connection

- A connection is uniquely identified by the socket addresses of its endpoints (socket pair)
  - (cliaddr:cliport, servaddr:servport)

**Client socket address**
128.2.194.242:51213

**Server socket address**
208.216.181.15:80

**Client host address**
128.2.194.242

**Server host address**
208.216.181.15

- 51213 is an ephemeral port allocated by the kernel
- 80 is a well-known port associated with Web servers
Using Ports to Identify Services

Service request for 128.2.194.242:80 (i.e., the Web server)

Service request for 128.2.194.242:7 (i.e., the Echo server)
Sockets Interface

- Set of system-level functions used in conjunction with Unix I/O to build network applications.

- Created in the early 80’s as part of the original Berkeley distribution of Unix that contained an early version of the Internet protocols.

- Available on all modern systems
  - Unix variants, Windows, OS X, IOS, Android, ARM

- **Sockets** are communication endpoints. They are represented to the application as a file descriptor, but are opened using different functions than for files.
Berkeley Sockets API demo
Additional slides
(1) IP Addresses

- 32-bit IP addresses are stored in an **IP address struct**
  - IP addresses are always stored in memory in **network byte order** (big-endian byte order)
  - True in general for any integer transferred in a packet header from one machine to another.
    - E.g., the port number used to identify an Internet connection.

```c
/* Internet address structure */
struct in_addr {
    uint32_t  s_addr; /* network byte order (big-endian) */
};
```
Dotted Decimal Notation

- By convention, each byte in a 32-bit IP address is represented by its decimal value and separated by a period
  - IP address: \(0x8002C2F2 = 128.2.194.242\)

- Use `getaddrinfo` and `getnameinfo` functions (described later) to convert between IP addresses and dotted decimal format.
(2) Internet Domain Names

unamed root

- .net
- .edu
- .gov
- .com

First-level domain names

- mit
- cmu
- berkeley
- amazon

Second-level domain names

- cs
- ece
- www 54.239.25.208

Third-level domain names

- ics
- pdl

whaleshark 128.2.210.175
- www 128.2.131.66
Domain Naming System (DNS)

- The Internet maintains a mapping between IP addresses and domain names in a huge worldwide distributed database called **DNS**.

- Conceptually, programmers can view the DNS database as a collection of millions of **host entries**.
  - Each host entry defines the mapping between a set of domain names and IP addresses.
  - In a mathematical sense, a host entry is an equivalence class of domain names and IP addresses.
Properties of DNS Mappings

- Can explore properties of DNS mappings using `nslookup`
  - Output edited for brevity

- Each host has a locally defined domain name `localhost` which always maps to the *loopback address* `127.0.0.1`
  ```
  linux> nslookup localhost
  Address: 127.0.0.1
  ```

- Use `hostname` to determine real domain name of local host:
  ```
  linux> hostname
  whaleshark.ics.cs.cmu.edu
  ```
Properties of DNS Mappings (cont)

- Simple case: one-to-one mapping between domain name and IP address:

  ```
  linux> nslookup whaleshark.ics.cs.cmu.edu
  Address: 128.2.210.175
  ```

- Multiple domain names mapped to the same IP address:

  ```
  linux> nslookup cs.mit.edu
  Address: 18.62.1.6
  linux> nslookup eecs.mit.edu
  Address: 18.62.1.6
  ```
Properties of DNS Mappings (cont)

- Multiple domain names mapped to multiple IP addresses:

  ```
  linux> nslookup www.twitter.com
  Address: 104.244.42.65
  Address: 104.244.42.129
  Address: 104.244.42.193
  Address: 104.244.42.1
  ```

  ```
  linux> nslookup www.twitter.com
  Address: 104.244.42.129
  Address: 104.244.42.65
  Address: 104.244.42.193
  Address: 104.244.42.1
  ```

- Some valid domain names don’t map to any IP address:

  ```
  linux> nslookup ics.cs.cmu.edu
  *** Can't find ics.cs.cmu.edu: No answer
  ```
Anatomy of a Connection

- A connection is uniquely identified by the socket addresses of its endpoints (*socket pair*)
  - (cliaddr:cliport, servaddr:servport)

Client socket address: 128.2.194.242:51213

Server socket address: 208.216.181.15:80

Connection socket pair: (128.2.194.242:51213, 208.216.181.15:80)

Client host address: 128.2.194.242

Server host address: 208.216.181.15

51213 is an ephemeral port allocated by the kernel

80 is a well-known port associated with Web servers
Using Ports to Identify Services

Service request for 128.2.194.242:80 (i.e., the Web server)

Service request for 128.2.194.242:7 (i.e., the echo server)
Sockets Interface

- Set of system-level functions used in conjunction with Unix I/O to build network applications.

- Created in the early 80’s as part of the original Berkeley distribution of Unix that contained an early version of the Internet protocols.

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- *Sockets* are communication endpoints. They are represented to the application as a file descriptor, but are opened using different functions than for files.
Sockets

What is a socket?
- To the kernel, a socket is an endpoint of communication
- To an application, a socket is a file descriptor that lets the application read/write from/to the network
  - *Remember:* All Unix I/O devices, including networks, are modeled as files

Clients and servers communicate with each other by reading from and writing to socket descriptors

The main distinction between regular file I/O and socket I/O is how the application “opens” the socket descriptors
Socket Programming Example

- Echo server and client
- Server
  - Accepts connection request
  - Repeats back lines as they are typed
- Client
  - Requests connection to server
  - Repeatedly:
    - Read line from terminal
    - Send to server
    - Read reply from server
    - Print line to terminal
Echo Server/Client Session Example

Client

```
bambooshark: ./echoclient whaleshark.ics.cs.cmu.edu 6616
This line is being echoed
This line is being echoed
This one is, too
This one is, too
^D
bambooshark: ./echoclient whaleshark.ics.cs.cmu.edu 6616
This one is a new connection
This one is a new connection
^D
```

Server

```
whaleshark: ./echoserveri 6616
Connected to (BAMBOOSHARK.ICS.CS.CMU.EDU, 33707)
server received 26 bytes
server received 17 bytes
Connected to (BAMBOOSHARK.ICS.CS.CMUCMU.EDU, 33708)
server received 29 bytes
```
1. Start server

Client

2. Start client

Server

Exchange data

Connect request

Await connection request from client

Close

EOF

4. Disconnect client

5. Drop client

Echo Server + Client Structure
1. Start server

Server

- `open_listenfd`

2. Start client

Client

- `open_clientfd`

3. Exchange data

- `fget`
- `rio_readlineb`
- `rio_writen`
- `fputs`
- `fgets`
- `rio_readlineb`

4. Disconnect client

- `close`

5. Drop client

- `close`
#include "csapp.h"

int main(int argc, char **argv)
{
    int clientfd;
    char *host, *port, buf[MAXLINE];
    rio_t rio;

    host = argv[1];
    port = argv[2];

    clientfd = Open_clientfd(host, port);
    Rio_readinitb(&rio, clientfd);

    while (Fgets(buf, MAXLINE, stdin) != NULL) {
        Rio_writen(clientfd, buf, strlen(buf));
        Rio_readlineb(&rio, buf, MAXLINE);
        Fputs(buf, stdout);
    }
    Close(clientfd);
    exit(0);
}
Iterative Echo Server: Main Routine

```c
#include "csapp.h"
void echo(int connfd);

int main(int argc, char **argv)
{
    int listenfd, connfd;
    socklen_t clientlen;
    struct sockaddr_storage clientaddr; /* Enough room for any addr */

    char client_hostname[MAXLINE], client_port[MAXLINE];

    listenfd = Open_listenfd(argv[1]);
    while (1) {
        clientlen = sizeof(struct sockaddr_storage); /* Important! */
        connfd = Accept(listenfd, (SA *)&clientaddr, &clientlen);
        Getnameinfo((SA *)&clientaddr, clientlen,
                     client_hostname, MAXLINE, client_port, MAXLINE, 0);
        printf("Connected to (%s, %s)\n", client_hostname, client_port);
        echo(connfd);
        Close(connfd);
    }
    exit(0);
}
```

Echo Server: echo function

- The server uses RIO to read and echo text lines until EOF (end-of-file) condition is encountered.
  - EOF condition caused by client calling `close(clientfd)`

```c
void echo(int connfd)
{
    size_t n;
    char buf[MAXLINE];
    rio_t rio;

    Rio_readinitb(&rio, connfd);
    while((n = Rio_readlineb(&rio, buf, MAXLINE)) != 0) {
        printf("server received %d bytes\n", (int)n);
        Rio_writen(connfd, buf, n);
    }
}
```

The server uses RIO to read and echo text lines until EOF (end-of-file) condition is encountered.
- EOF condition caused by client calling `close(clientfd)`
Socket Address Structures

Generic socket address:

- For address arguments to `connect`, `bind`, and `accept`
- Necessary only because C did not have generic (`void *`) pointers when the sockets interface was designed
- For casting convenience, we adopt the Stevens convention:
  ```
typedef struct sockaddr SA;
  ```

```c
typedef struct sockaddr {
    uint16_t   sa_family; /* Protocol family */
    char       sa_data[14];  /* Address data. */
} SA;
```

`sa_family`
Socket Address Structures

- **Internet (IPv4) specific socket address:**
  - Must cast `(struct sockaddr_in *)` to `(struct sockaddr *)` for functions that take socket address arguments.

```c
struct sockaddr_in {
    uint16_t sin_family;    /* Protocol family (always AF_INET) */
    uint16_t sin_port;      /* Port num in network byte order */
    struct in_addr sin_addr; /* IP addr in network byte order */
    unsigned char sin_zero[8]; /* Pad to sizeof(struct sockaddr) */
};
```

<table>
<thead>
<tr>
<th>sa_family</th>
<th>sin_port</th>
<th>sin_addr</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF_INET</td>
<td></td>
<td>0 0 0 0 0 0 0 0 0 0</td>
</tr>
</tbody>
</table>

**sin_family**

**Family Specific**
Host and Service Conversion: `getaddrinfo`

- `getaddrinfo` is the modern way to convert string representations of hostnames, host addresses, ports, and service names to socket address structures.
  - Replaces obsolete `gethostbyname` and `getservbyname` funcs.

- Advantages:
  - Reentrant (can be safely used by threaded programs).
  - Allows us to write portable protocol-independent code
    - Works with both IPv4 and IPv6

- Disadvantages
  - Somewhat complex
  - Fortunately, a small number of usage patterns suffice in most cases.
Host and Service Conversion: getaddrinfo

Given host and service, getaddrinfo returns result that points to a linked list of addrinfo structs, each of which points to a corresponding socket address struct, and which contains arguments for the sockets interface functions.

Helper functions:
- freeaddrinfo frees the entire linked list.
- gai_strerror converts error code to an error message.
Clients: walk this list, trying each socket address in turn, until the calls to `socket` and `connect` succeed.

Servers: walk the list until calls to `socket` and `bind` succeed.
### addrinfo Struct

```c
struct addrinfo {
    int ai_flags;      /* Hints argument flags */
    int ai_family;     /* First arg to socket function */
    int ai_socktype;   /* Second arg to socket function */
    int ai_protocol;   /* Third arg to socket function */
    char *ai_canonname; /* Canonical host name */
    size_t ai_addrlen; /* Size of ai_addr struct */
    struct sockaddr *ai_addr; /* Ptr to socket address structure */
    struct addrinfo *ai_next; /* Ptr to next item in linked list */
};
```

- Each `addrinfo` struct returned by `getaddrinfo` contains arguments that can be passed directly to `socket` function.
- Also points to a socket address struct that can be passed directly to `connect` and `bind` functions.
Host and Service Conversion: getnameinfo

- `getnameinfo` is the inverse of `getaddrinfo`, converting a socket address to the corresponding host and service.
  - Replaces obsolete `gethostbyaddr` and `getservbyport` funcs.
  - Reentrant and protocol independent.

```c
int getnameinfo(const SA *sa, socklen_t salen, /* In: socket addr */
                char *host, size_t hostlen,       /* Out: host */
                char *serv, size_t servlen,      /* Out: service */
                int flags);                       /* optional flags */
```
Conversion Example

```c
#include "csapp.h"

int main(int argc, char **argv)
{
    struct addrinfo *p, *listp, hints;
    char buf[MAXLINE];
    int rc, flags;

    /* Get a list of addrinfo records */
    memset(&hints, 0, sizeof(struct addrinfo));
    hints.ai_family = AF_INET;    /* IPv4 only */
    hints.ai_socktype = SOCK_STREAM; /* Connections only */
    if ((rc = getaddrinfo(argv[1], NULL, &hints, &listp)) != 0) {
        fprintf(stderr, "getaddrinfo error: %s\n", gai_strerror(rc));
        exit(1);
    }
}
```

hostinfo.c
Conversion Example (cont)

```c
/* Walk the list and display each IP address */
flags = NI_NUMERICHOST; /* Display address instead of name */
for (p = listp; p; p = p->ai_next) {
    Getnameinfo(p->ai_addr, p->ai_addrlen,
                buf, MAXLINE, NULL, 0, flags);
    printf("%s\n", buf);
}

/* Clean up */
Freeaddrinfo(listp);
exit(0);
```
Running hostinfo

```
whaleshark> ./hostinfo localhost
127.0.0.1

whaleshark> ./hostinfo whaleshark.ics.cs.cmu.edu
128.2.210.175

whaleshark> ./hostinfo twitter.com
199.16.156.230
199.16.156.38
199.16.156.102
199.16.156.198
```
Next time

- Using *getaddrinfo* for host and service conversion
- Writing clients and servers
- Writing Web servers!
Basic Internet Components

- **Internet backbone:**
  - collection of routers (nationwide or worldwide) connected by high-speed point-to-point networks

- **Internet Exchange Points (IXP):**
  - router that connects multiple backbones (often referred to as peers)
  - Also called Network Access Points (NAP)

- **Regional networks:**
  - smaller backbones that cover smaller geographical areas (e.g., cities or states)

- **Point of presence (POP):**
  - machine that is connected to the Internet

- **Internet Service Providers (ISPs):**
  - provide dial-up or direct access to POPs
Internet Connection Hierarchy

PRIVATE "peering" agreements between two backbone companies often bypass IXP

Colocation sites

ISP (for individuals)  \(\rightarrow\) Regional net  \(\rightarrow\) Backbone  \(\rightarrow\) IXP  \(\rightarrow\) Backbone  \(\rightarrow\) POP

Small Business  \(\rightarrow\) ISP  \(\rightarrow\) POP  \(\rightarrow\) POP

Big Business  \(\rightarrow\) POP  \(\rightarrow\) POP  \(\rightarrow\) POP

Pgh employee  \(\rightarrow\) POP  \(\rightarrow\) POP  \(\rightarrow\) POP

DC employee  \(\rightarrow\) POP  \(\rightarrow\) POP  \(\rightarrow\) POP

ISP (for individuals)  \(\rightarrow\) Regional net  \(\rightarrow\) Backbone  \(\rightarrow\) IXP  \(\rightarrow\) Backbone  \(\rightarrow\) POP

Small Business  \(\rightarrow\) ISP  \(\rightarrow\) POP  \(\rightarrow\) POP

Big Business  \(\rightarrow\) POP  \(\rightarrow\) POP  \(\rightarrow\) POP

Pgh employee  \(\rightarrow\) POP  \(\rightarrow\) POP  \(\rightarrow\) POP

DC employee  \(\rightarrow\) POP  \(\rightarrow\) POP  \(\rightarrow\) POP
IP Address Structure

- **IP (V4) Address space divided into classes:**

  - Class A: 0
  - Class B: 10
  - Class C: 110
  - Class D: 1110
  - Class E: 1111

  ![IP Address Structure Diagram](image)

  - Network ID Written in form w.x.y.z/n
    - n = number of bits in host address
    - E.g., CMU written as 128.2.0.0/16
      - Class B address

  - **Unrouted (private) IP addresses:**
    - 10.0.0.0/8
    - 172.16.0.0/12
    - 192.168.0.0/16
Evolution of Internet

- Original Idea
  - Every node on Internet would have unique IP address
    - Everyone would be able to talk directly to everyone
  - No secrecy or authentication
    - Messages visible to routers and hosts on same LAN
    - Possible to forge source field in packet header

- Shortcomings
  - There aren't enough IP addresses available
  - Don't want everyone to have access or knowledge of all other hosts
  - Security issues mandate secrecy & authentication
Evolution of Internet: Naming

- **Dynamic address assignment**
  - Most hosts don't need to have known address
    - Only those functioning as servers
  - DHCP (Dynamic Host Configuration Protocol)
    - Local ISP assigns address for temporary use

- **Example:**
  - Laptop at CMU (wired connection)
    - IP address 128.2.213.29 (**bryant-tp4.cs.cmu.edu**)  
    - Assigned statically
  - Laptop at home
    - IP address 192.168.1.5
    - Only valid within home network
**Evolution of Internet: Firewalls**

- **Firewalls**
  - Hides organizations nodes from rest of Internet
  - Use local IP addresses within organization
  - For external service, provides proxy service

1. Client request: src=10.2.2.2, dest=216.99.99.99
2. Firewall forwards: src=176.3.3.3, dest=216.99.99.99
3. Server responds: src=216.99.99.99, dest=176.3.3.3
4. Firewall forwards response: src=216.99.99.99, dest=10.2.2.2