15-213
“The course that gives CMU its Zip!”

Internetworking
November 6, 2003

Topics
- Client-server programming model
- Networks
- Internetworks
- Global IP Internet
- IP addresses
- Domain names
- Connections

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.

1. Client sends request
2. Server sends response
3. Server handles request
4. Client handles response

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

Hardware Org of a Network Host

Computer Networks

A network is a hierarchical system of boxes and wires organized by geographical proximity
- SAN (System Area Network) spans cluster or machine room
- Switched Ethernet, Quadrics QSW, ...
- 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 point-to-point phone lines.

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 we would build an internet from the ground up.
Lowest Level: Ethernet Segment

Ethernet segment consists of a collection of hosts connected by wires (twisted pairs) to a hub.

- Spans room or floor in a building.
- Each Ethernet adapter has a unique 48-bit address.
- Hosts send bits to any other host in chunks called frames.
- Hub slavishly copies each bit from each port to every other port.

Note: Hubs are on their way out. Bridges (switches, routers) became cheap enough to replace them (means no more broadcasting).

Next Level: Bridged Ethernet Segment

- Spans building or campus.
- Bridges cleverly learn which hosts are reachable from which ports and then selectively copy frames from port to port.

Conceptual View of LANs

- For simplicity, hubs, bridges, and wires are often shown as a collection of hosts attached to a single wire.

Next Level: Internets

- Multiple incompatible LANs can be physically connected by specialized computers called routers.
- The connected networks are called an internet.

LAN 1 and LAN 2 might be completely different, totally incompatible LANs (e.g., Ethernet and WiFi, 802.11*, T1-links, DSL, ...).
The Notion of an Internet Protocol

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

Solution: protocol software running on each host and router smooths out the differences between the different networks.

Implements an internet protocol (i.e., a set of rules) that governs how hosts and routers should cooperate when they transfer data from network to network. TCP/IP is the protocol for the global IP Internet.

What Does an Internet Protocol Do?

1. 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.

2. 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.

Transferring Data Over an Internet

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

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.

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Hardware and Software Org of an Internet Application

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Basic Internet Components

- An Internet backbone is a collection of routers (nationwide or worldwide) connected by high-speed point-to-point networks.
- A Network Access Point (NAP) is a router that connects multiple backbones (sometimes referred to as peers).
- Regional networks are smaller backbones that cover smaller geographical areas (e.g., cities or states)
- A point of presence (POP) is a machine that is connected to the Internet.
- Internet Service Providers (ISPs) provide dial-up or direct access to POPs.

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The Internet Circa 1986

In 1986, the Internet consisted of one backbone (NSFNET) that connected 13 sites via 45 Mbs T3 links.

- Merit (Univ of Mich), NCSA (Illinois), Cornell Theory Center, Pittsburgh Supercomputing Center, San Diego Supercomputing Center, John von Neumann Center (Princeton), BARRNet (Palo Alto), MidNet (Lincoln, NE), WestNet (Salt Lake City), NorthwestNet (Seattle), SESQUINET (Rice), SURANET (Georgia Tech).

Connecting to the Internet involved connecting one of your routers to a router at a backbone site, or to a regional network that was already connected to the backbone.
NSFNET Internet Backbone

Current NAP-Based Internet Architecture

In the early 90’s commercial outfits were building their own high-speed backbones, connecting to NSFNET, and selling access to their POPs to companies, ISPs, and individuals.

In 1995, NSF decommissioned NSFNET, and fostered creation of a collection of NAPs to connect the commercial backbones.

Currently in the US there are about 50 commercial backbones connected by ~12 NAPs (peering points).

Similar architecture worldwide connects national networks to the Internet.

Internet Connection Hierarchy

Network Access Points (NAPs)

Note: Peers in this context are commercial backbones...
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 {
    unsigned int s_addr; /* network byte order (big-endian) */
};
```

Handy network byte-order conversion functions:
- htonl: convert long int from host to network byte order.
- htons: convert short int from host to network byte order.
- ntohl: convert long int from network to host byte order.
- ntohs: convert short int from network to host byte order.

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2. 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 0xe002c0f2 = 128.2.194.242

Functions for converting between binary IP addresses and dotted decimal strings:
- inet_aton: converts a dotted decimal string to an IP address in network byte order.
- inet_ntoa: converts an IP address in network byte order to its corresponding dotted decimal string.
- "n" denotes network representation, "a" denotes application representation.

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

2. The set of IP addresses is mapped to a set of identifiers called Internet domain names.
   - 128.2.203.179 is mapped to www.cs.cmu.edu

3. A process on one Internet host can communicate with a process on another Internet host over a connection.
**IP Address Structure**

IP (V4) Address space divided into classes:

<table>
<thead>
<tr>
<th>Class</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>8</th>
<th>16</th>
<th>24</th>
<th>31</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Net ID</td>
<td>Host ID</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Net ID</td>
<td>Host ID</td>
<td></td>
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</tr>
<tr>
<td>C</td>
<td>Net ID</td>
<td>Host ID</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Multicast address</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Reserved for experiments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Special Addresses for routers and gateways (all 0/1’s)

Loop-back address: 127.0.0.1

Unrouted (private) IP addresses:

10.0.0.0/8   172.16.0.0/12   192.168.0.0/16

Dynamic IP addresses (DHCP)

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**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 entry structures:

```c
/* DNS host entry structure */
struct hostent {  
    char *h_name;     /* official domain name of host */  
    char **h_aliases; /* null-terminated array of domain names */  
    int h_type;       /* host address type (AF_INET) */  
    int h_length;     /* length of an address, in bytes */  
    char **h_addr_list; /* null-terminated array of in_addr structs */  
};
```

Functions for retrieving host entries from DNS:

- `gethostbyname`: query key is a DNS domain name.
- `gethostbyaddr`: query key is an IP address.

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**Properties of DNS Host Entries**

Each host entry is an equivalence class of domain names and IP addresses.

Each host has a locally defined domain name `localhost` which always maps to the loopback address 127.0.0.1

Different kinds of mappings are possible:

- Simple case: 1-1 mapping between domain name and IP addr:
  - `kittyhawk.cs.cmu.edu` maps to 128.2.194.242

- Multiple domain names mapped to the same IP address:
  - `ecs.mit.edu` and `cs.mit.edu` both map to 18.62.1.6

- Multiple domain names mapped to multiple IP addresses:
  - `aol.com` and `www.aol.com` map to multiple IP addr.

- Some valid domain names don’t map to any IP address:
  - For example: `cneio.cs.cmu.edu`

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A Program That Queries DNS

```c
int main(int argc, char **argv) {  /* argv[1] is a domain name */
    char **pp;
    * or dotted decimal IP addr */
    struct in_addr addr;
    struct hostent *hostp;

    if (inet_aton(argv[1], &addr) != 0) {
        hostp = gethostbyaddr((const char *)&addr, sizeof(addr), AF_INET);
    } else {
        hostp = gethostbyname(argv[1]);
        printf("official hostname: ", hostp->h_name);
        for (pp = hostp->h_aliases; *pp != NULL; pp++)
            printf("alias: ", *pp);
        for (pp = hostp->h_addr_list; *pp != NULL; pp++) {
            addr.s_addr = * (unsigned int *)pp;
            printf("address: %s", inet_ntoa(addr));
        }
    }
}
```

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3. Internet Connections

Clients and servers communicate by sending streams of bytes over connections:
- Point-to-point, full-duplex (2-way communication), and reliable.

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 on client 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)

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

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Querying DNS from the Command Line

Domain Information Groper (dig) provides a scriptable command line interface to DNS.

```
linux> dig +short kittyhawk.cmcl.cs.cmu.edu 128.2.194.242
KITTENAK.CMCL.CS.CMU.EDU.
linux> dig +short aol.com
205.188.150.215
205.188.160.121
64.12.149.24
64.12.187.25
linux> dig +short -x 64.12.187.25
aol-tv5.webdriver.aol.com.
```

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Putting it all Together: Anatomy of an Internet Connection

Client socket address 128.2.194.242:51213
Server socket address 208.216.58.15:80

Client host address 128.2.194.242
Server host address 208.216.58.15
Next Time

How to use the sockets interface to establish Internet connections between clients and servers
How to use Unix I/O to copy data from one host to another over an Internet connection.