COMPUTER NETWORKS

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Objectives

- Exposure to the basic underpinnings of the Internet
- Use network socket interfaces effectively

Network Security is a Massive Issue…

Daily, e.g. 110 attacks from China; 26 attacks from USA

2/2016 Hackers dumped the records of nearly 30,000 FBI and Department of Homeland Security workers.

1/2017 Hacking/Surveillance company Cellebrite lost 900GB of user data to a hac

9/2018 Facebook security breach exposes personal data of 50M users

Source: Akamai Technologies, Inc

Bottom-Line.....

- Internet is a ubiquitous presence in our lives
- Issues such as Security Lapses present themselves as **opportunities** for making our ways of communication more robust
- Let's now trace back the history from the early days of telephony in the next few slides

Telephony

Interactive telecommunication between people

Analog voice

- Transmitter/Receiver continuously in contact with electronic circuit
- Electric current varies with acoustic pressure

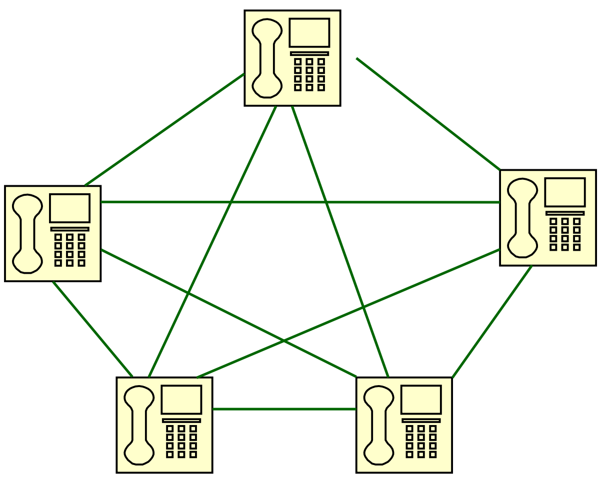
Analog/Continuous Signal

Telephony Milestones

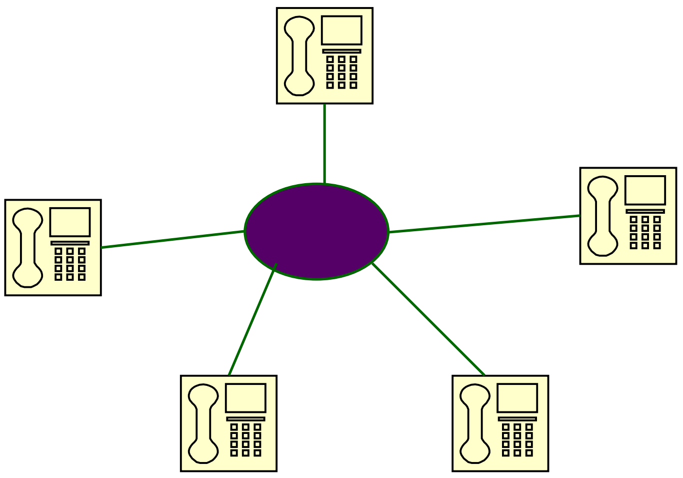
1876: Alexander Bell invented telephone

1878: Public switches installed at New Haven and San Francisco, public switched telephone network is born

- **People can talk without being on the same wire!**



Without Switch

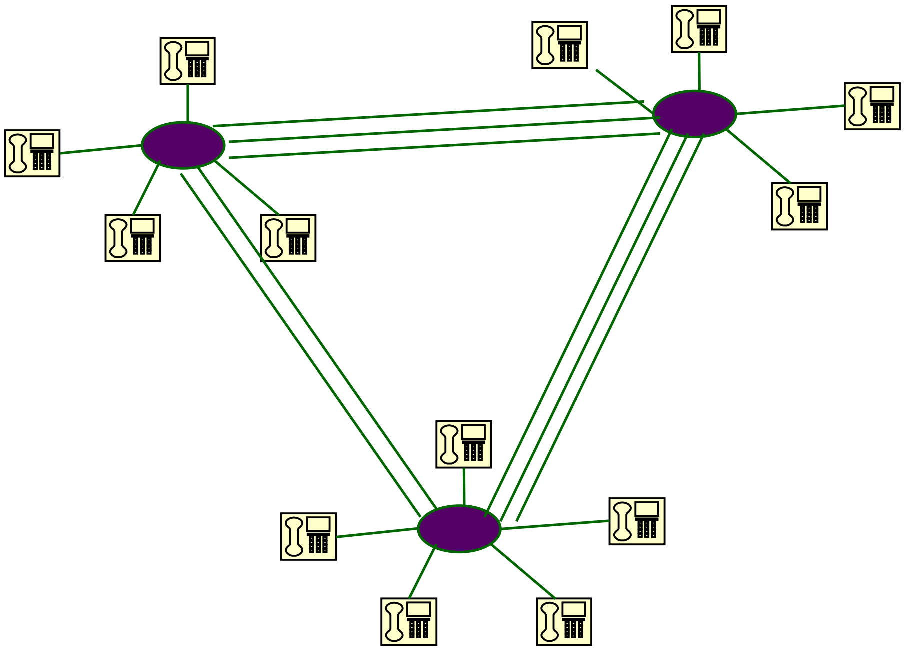


With Switch

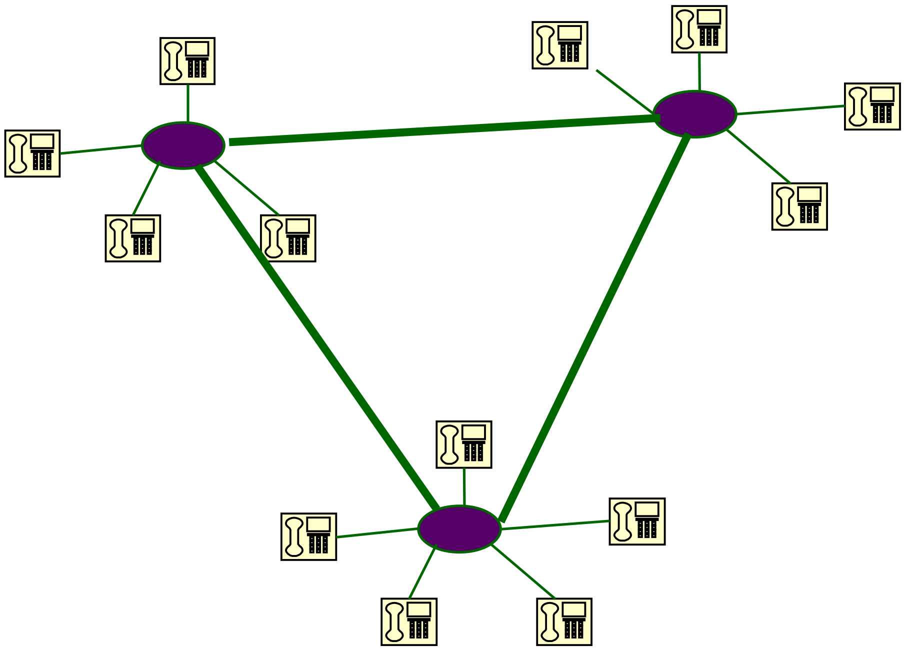
Telephony Milestones

1937: Multiplexing introduced for inter-city calls

- **One link carries multiple conversations**



Without Multiplexing



With Multiplexing

Data or Computer Networks

- Networks designed for computers to computers or devices
  - vs. communication between human beings
- Digital information
  - vs. analog voice

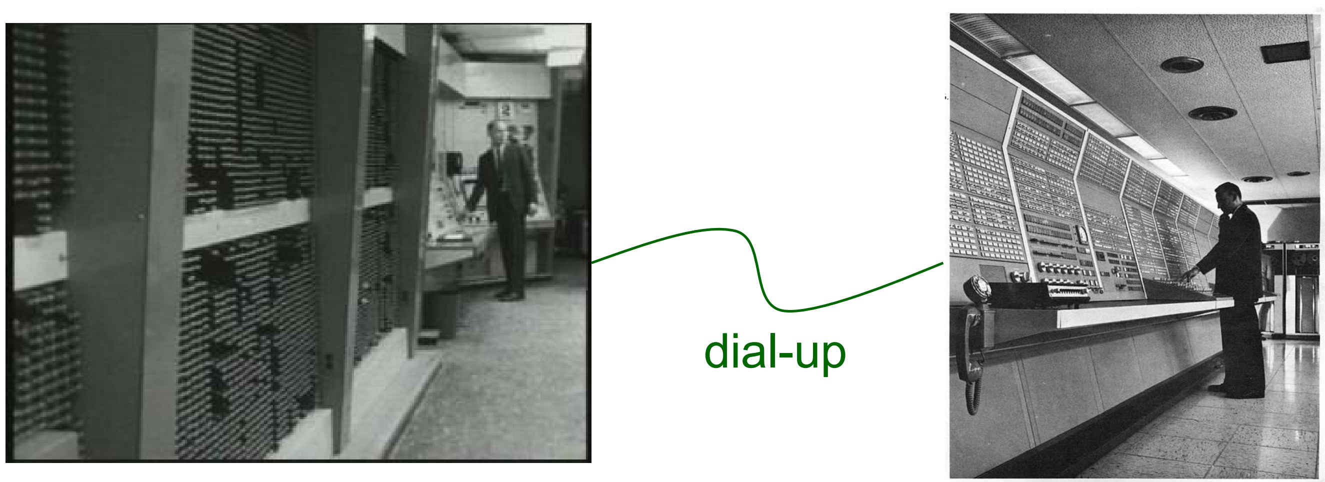
Digital/Discrete Signal

- Not a continuous stream of bits, rather, discrete “packets” with lots of silence in between
  - Dedicated circuit hugely inefficient

Major Internet Milestones

1960-1964 Basic concept of "packet switching" was independently developed by Baran (RAND), Kleinrock (MIT)

1965 First time two computers talked to each other using packets (Roberts, MIT; Marill, SDC)

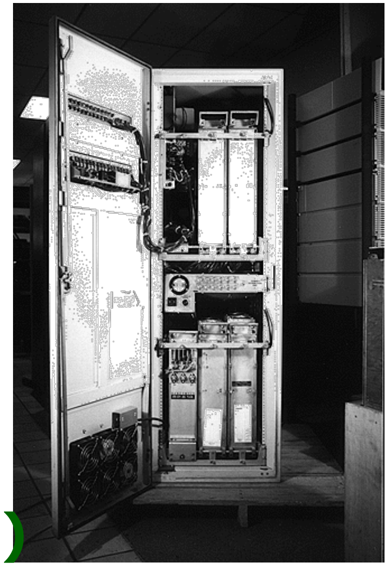


MIT TX-2

SDC Q32

Major Internet Milestones

1968 BBN group proposed to use Honeywell 516 mini-computers for the Interface Message Processors (i.e. packet switches)

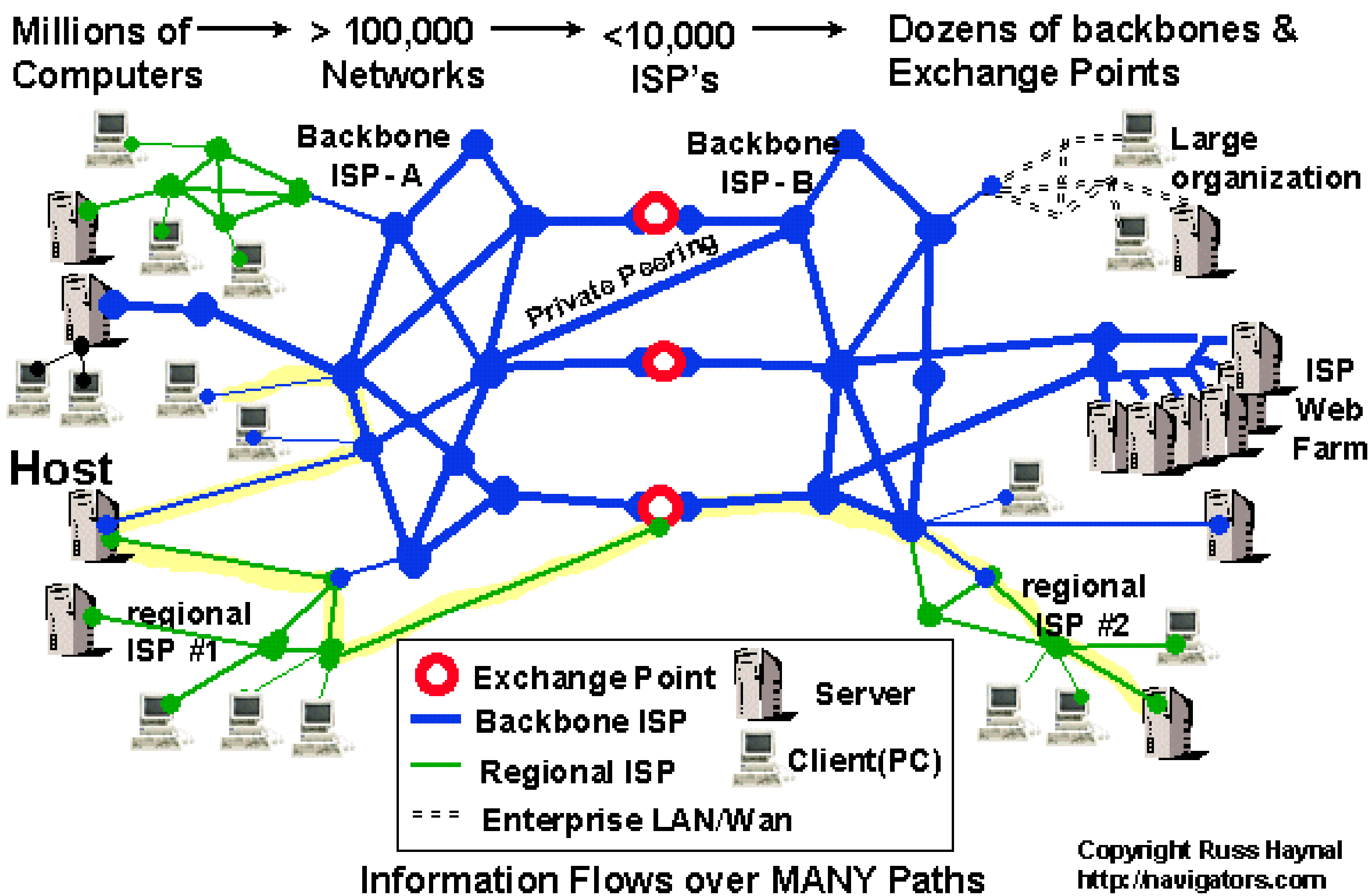


1969 The first ARPANET message transmitted between UCLA (Kleinrock) and SRI (Engelbart)

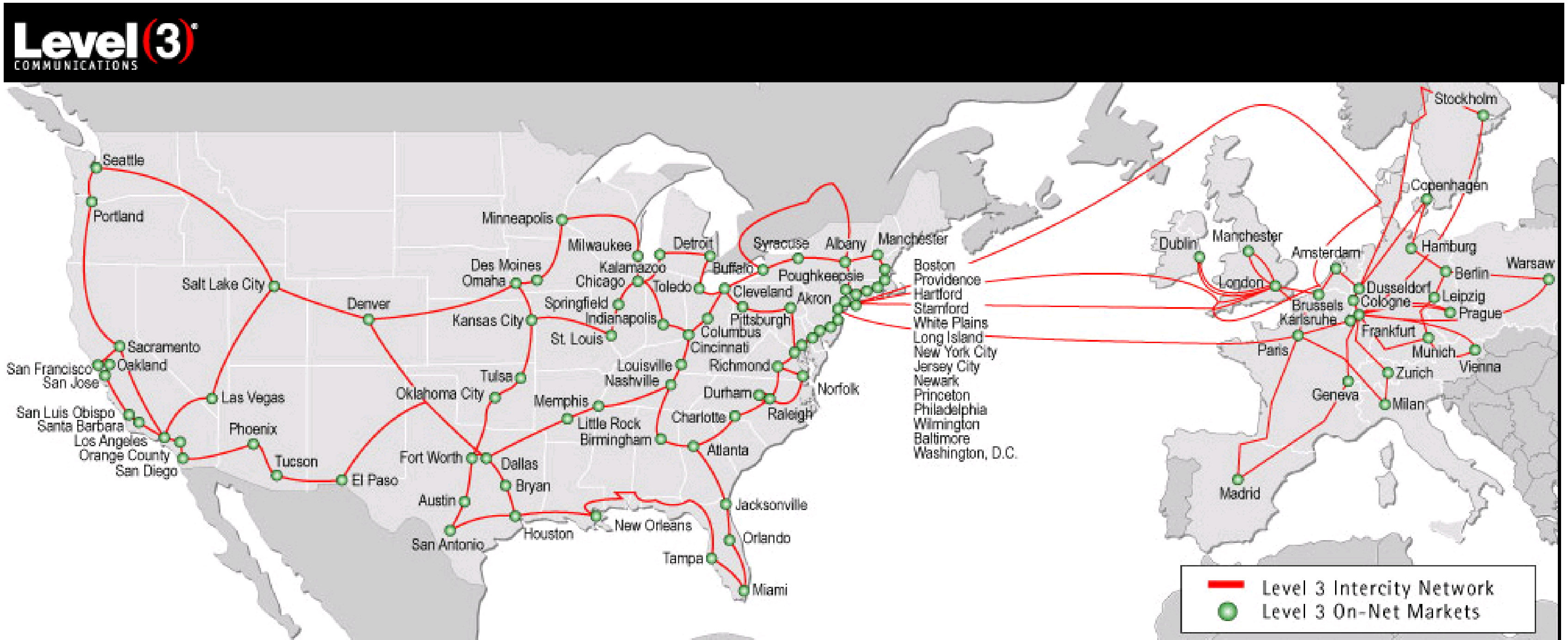
- **We sent an "L", did you get the "L"? Yep!**
- **We sent an "O", did you get the "O"? Yep!**
- **We sent a "G", did you get the "G"?**

An hour later, the first message "login" was successfully transmitted

Current Internet Architecture - Conceptual



Level 3 Backbone



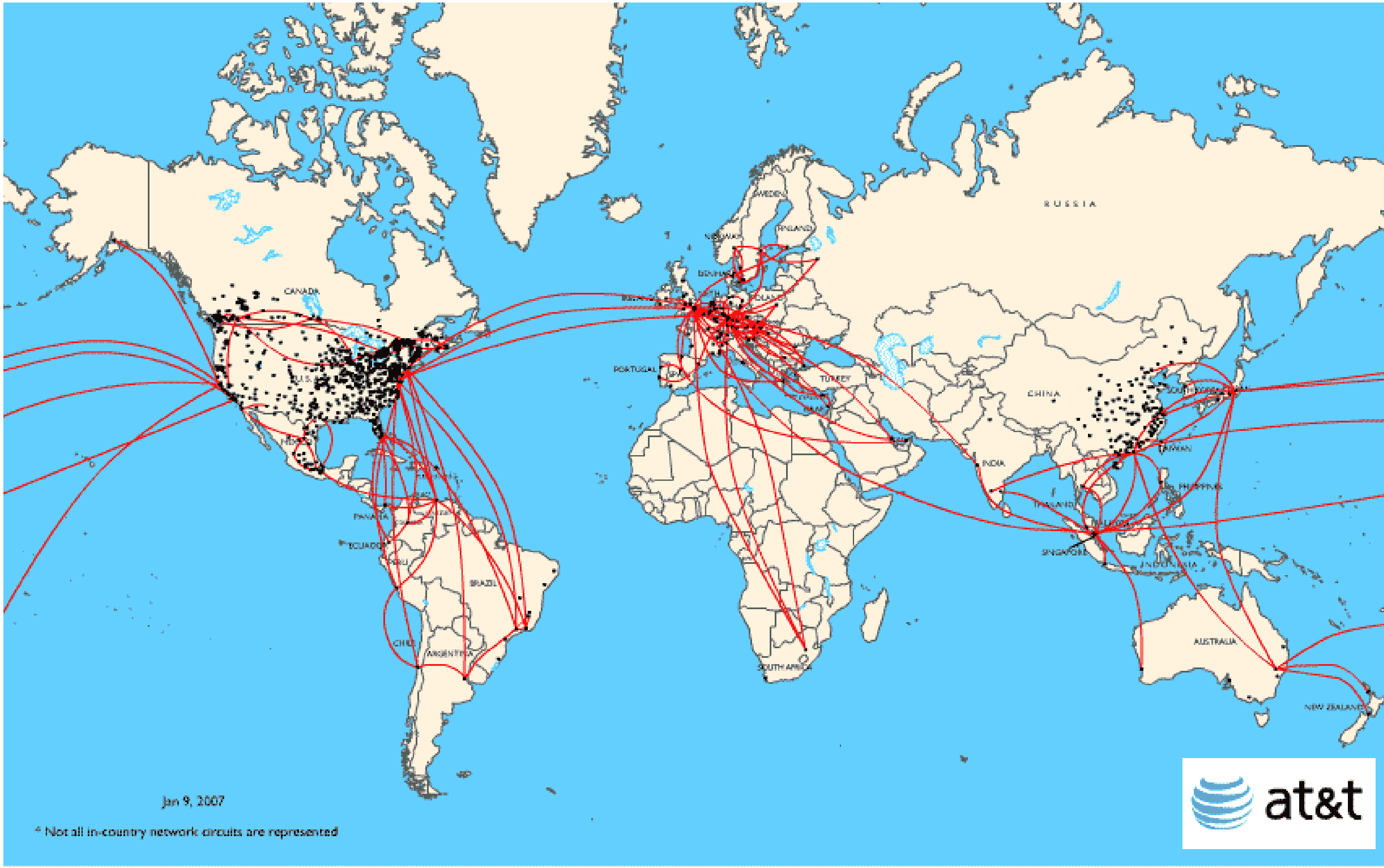
Metro Networks

Amsterdam	Chicago	Frankfurt	Miami	Paris	San Jose
Atlanta	Cincinnati	Hamburg	Munich	Philadelphia	Seattle
Baltimore	Dallas	Houston	Newark	Phoenix	St. Louis
Berlin	Denver	Jersey City	New York City	Portland	Stamford
Boston	Detroit	London	Orange County	San Diego	Tampa
Brussels	Dusseldorf	Los Angeles	Orlando	San Francisco	Washington, D.C.

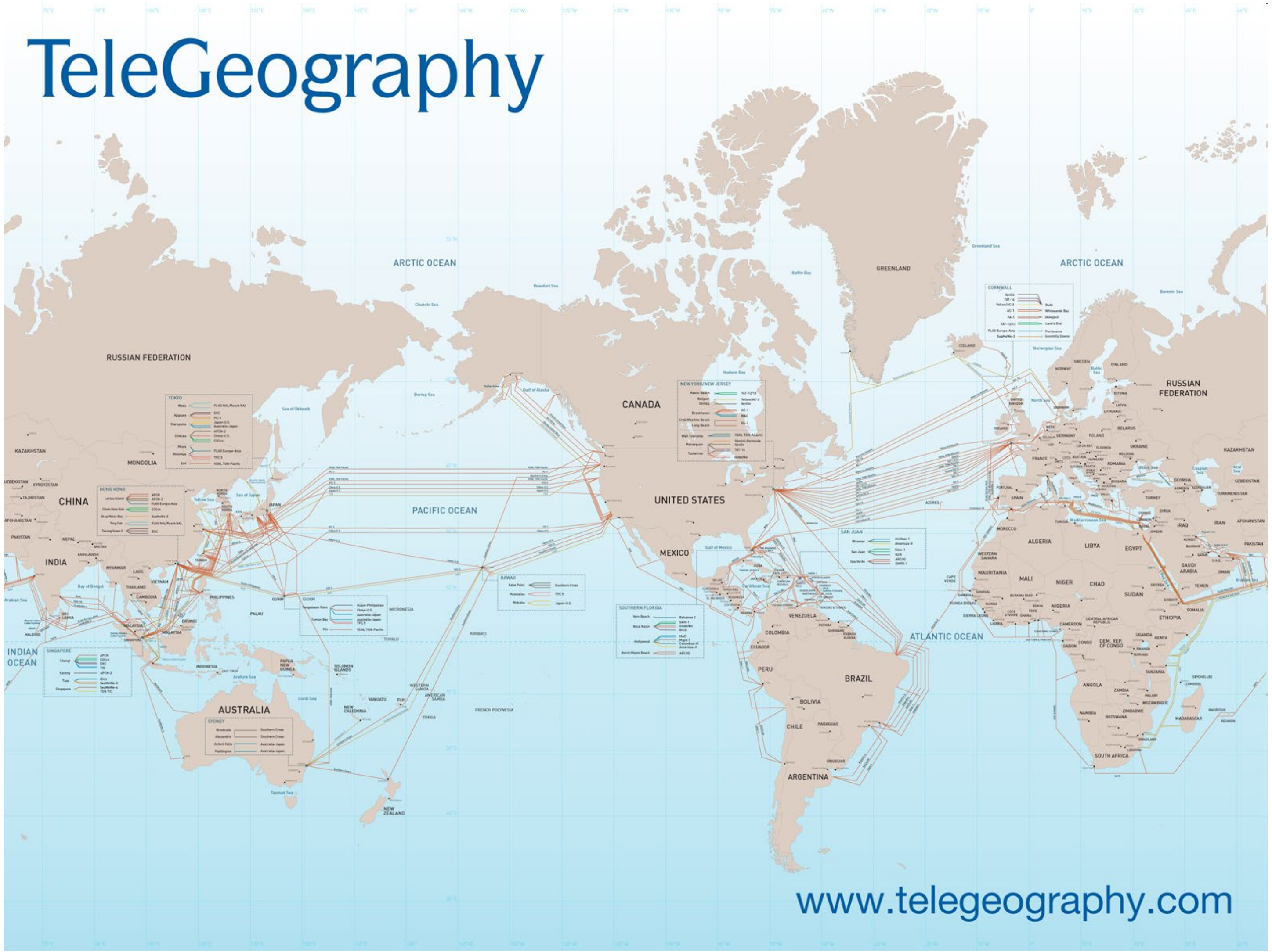
Network Statistics

- 23,000 intercity route miles
- 2,200 metropolitan route miles
- 947,000 miles of installed metro fiber
- 320 Gbps of transatlantic capacity
- 850 international points of presence
- 100 on-net markets
- 300+ voice markets

AT&T Backbone



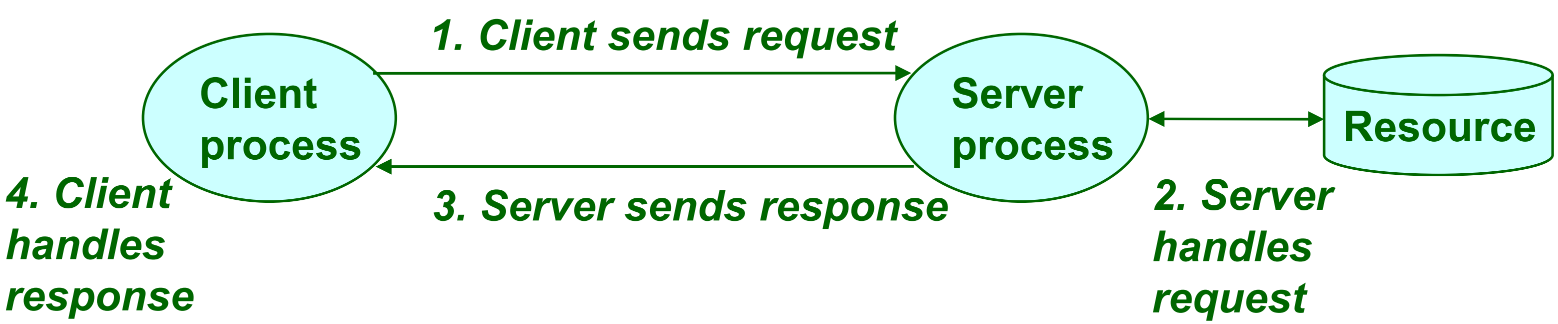
Submarine Cabling



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**



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

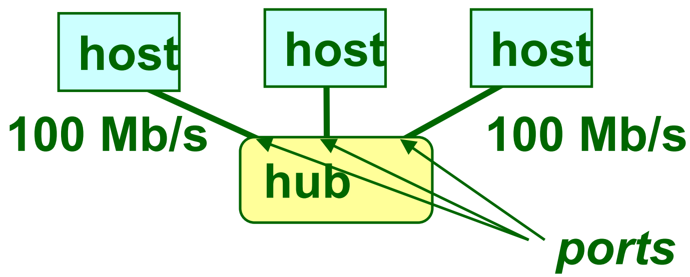
- Cluster network spans cluster or machine room
  - Switched Ethernet, Infiniband, …
- LAN (local area network) spans a building or campus
  - Ethernet is most prominent example
- WAN (wide-area network) spans very long distance
  - A high-speed point-to-point link
  - Leased line or SONET/SDH circuit, or MPLS/ATM circuit

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")

Lowest Level of Connectivity: Ethernet Segment

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

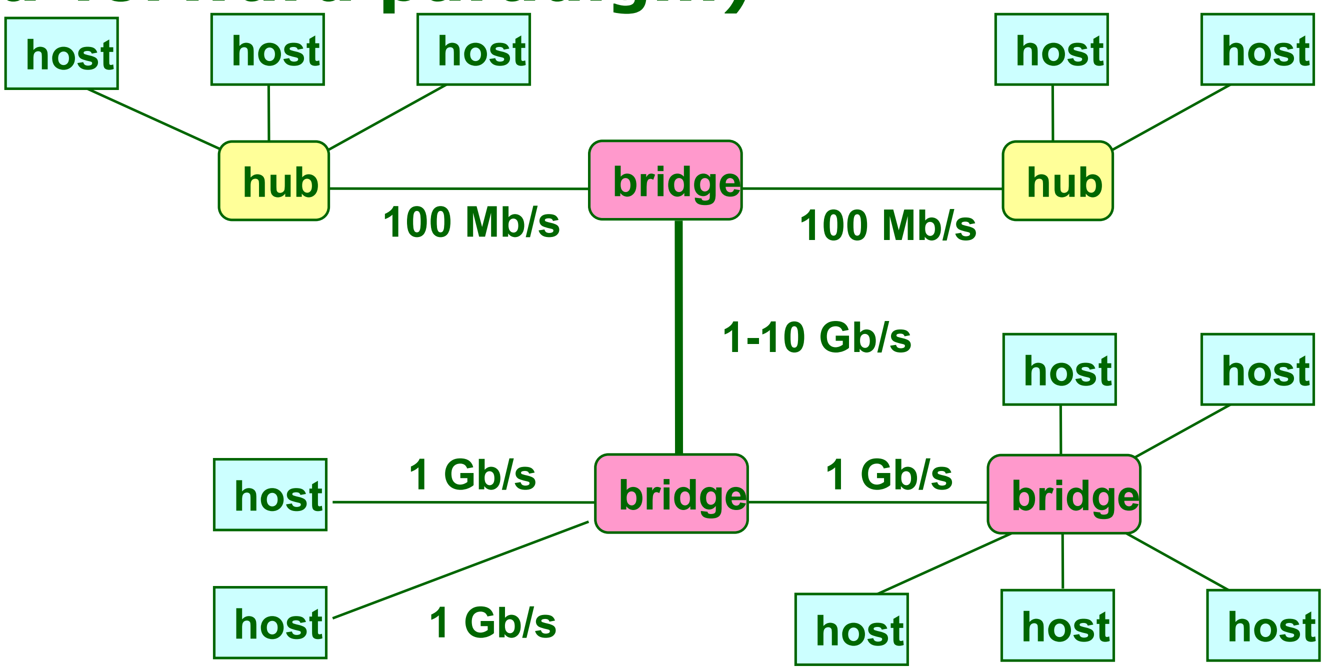


Operation

- Each Ethernet adapter has a unique 48-bit address
- Hosts send bits to any other host in chunks called frames
- Hub copies each bit from each port to every other port
  - Every host sees every bit
- Note: Hubs are largely obsolete
  - Bridges (switches, routers) became cheap enough to replace them (don't broadcast all traffic)

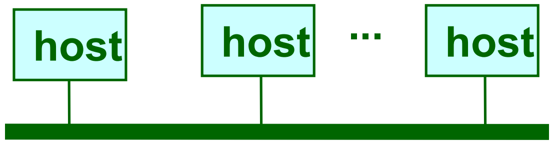
Next Level: Bridged Ethernet Segment

- Bridges cleverly learn which hosts are reachable from which ports.
- After that, any incoming packet is **stored temporarily** in incoming port buffer and then **selectively copied** into outgoing port (store-and-forward paradigm)



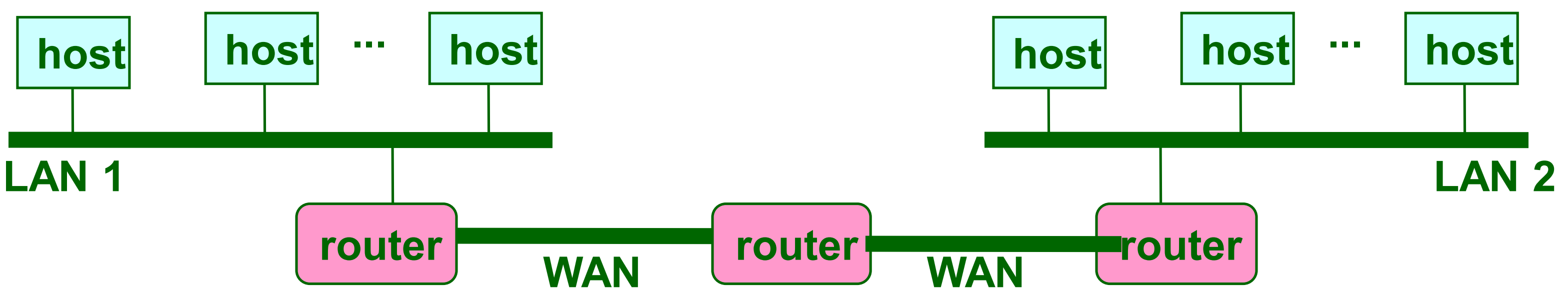
Conceptual View of LANs

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 smoothens out the differences between the different networks

Implements an internet protocol (i.e., 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?

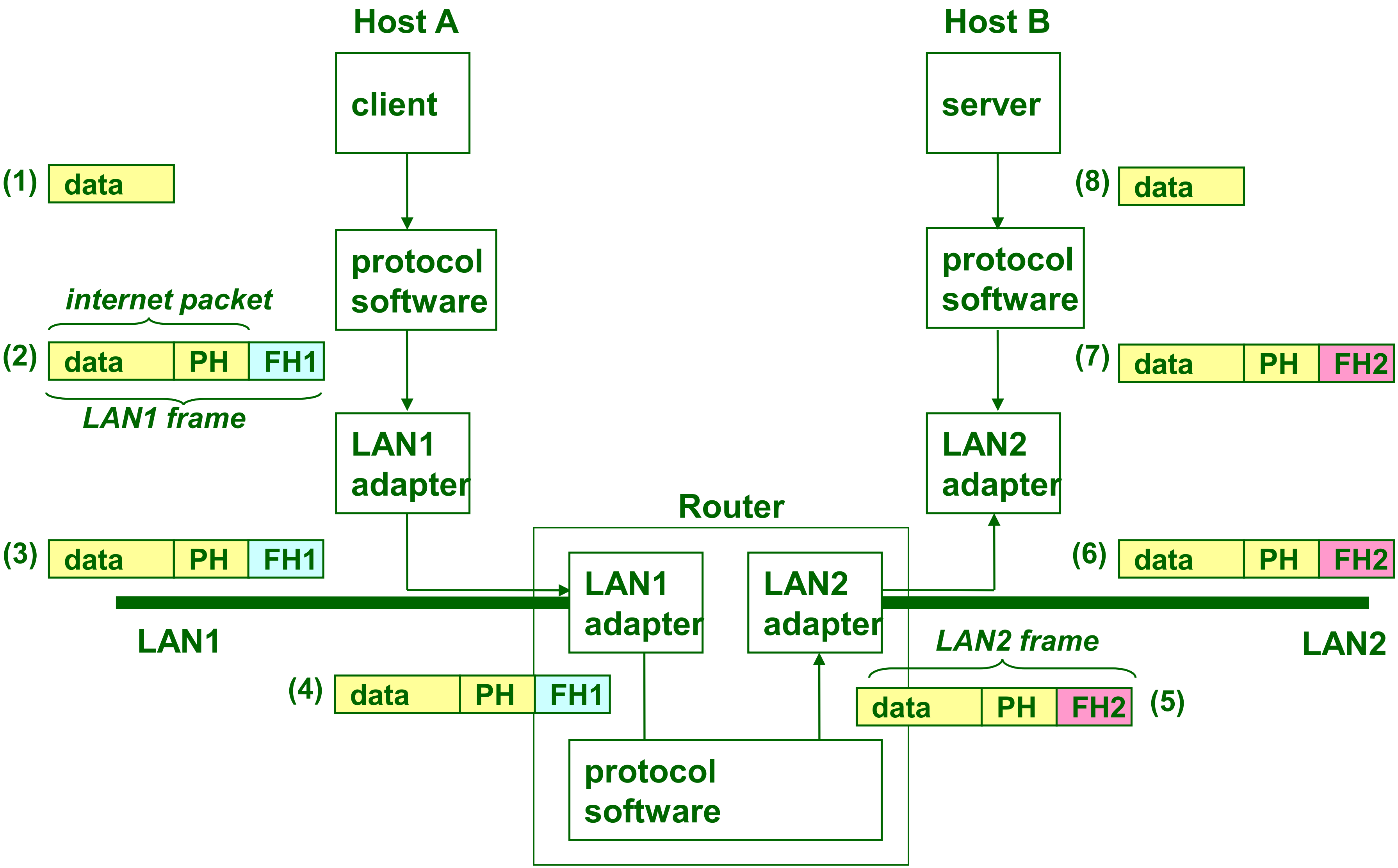
1. Provides a naming scheme

- 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

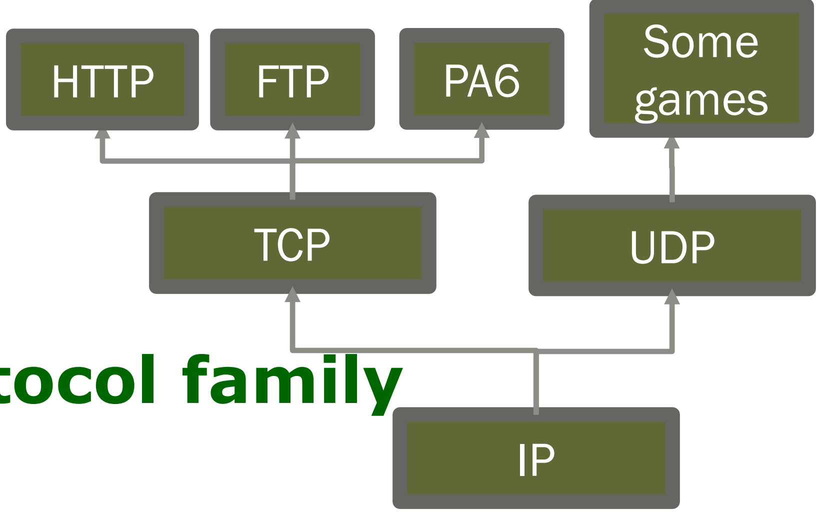
We are glossing over a number of important questions:

- 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?

We'll leave the discussion of these question to computer networking classes

→ CSCE 463

Global IP Internet

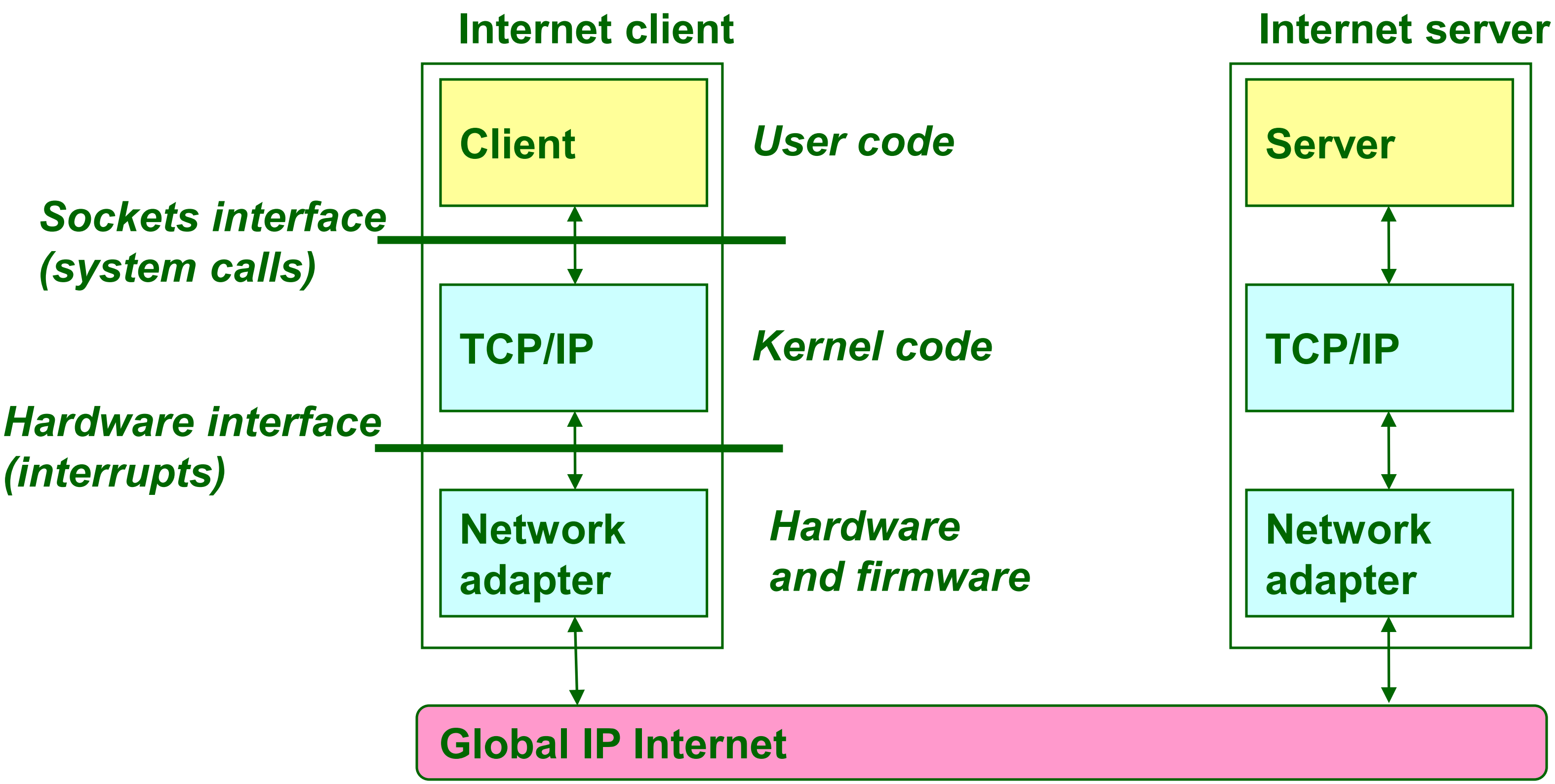


Based on the TCP/IP protocol family

- **IP (Internet protocol) :**
  - Provides basic naming scheme and unreliable delivery capability of packets (datagrams) from host-to-host
- **UDP (User 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

Organization of an Internet Application



A Programmer's View of the Internet

- Hosts are mapped to a set of 32-bit IP addresses
  - e.g. 128.194.255.88 (4 * 8 bits)
- A set of identifiers called Internet domain names are mapped to the set of IP addresses for convenience (Domain Name Server aka DNS)
  - linux2.cs.tamu.edu is mapped to 128.194.138.88
  - A process on one Internet host can communicate with a process on another Internet host over a connection

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)**
  - Big-endian means the most significant byte first, for instance a short 0x5F2D will be stored as 5F2D in that order
  - Little-endian means the opposite: 2D5F
- **True in general for any integer transferred in a packet header from one machine to another**

```
/* Internet address structure */
struct in_addr {
    unsigned int s_addr; /* network byte order (big-endian) */
};
```

Handy network byte-order conversion functions:

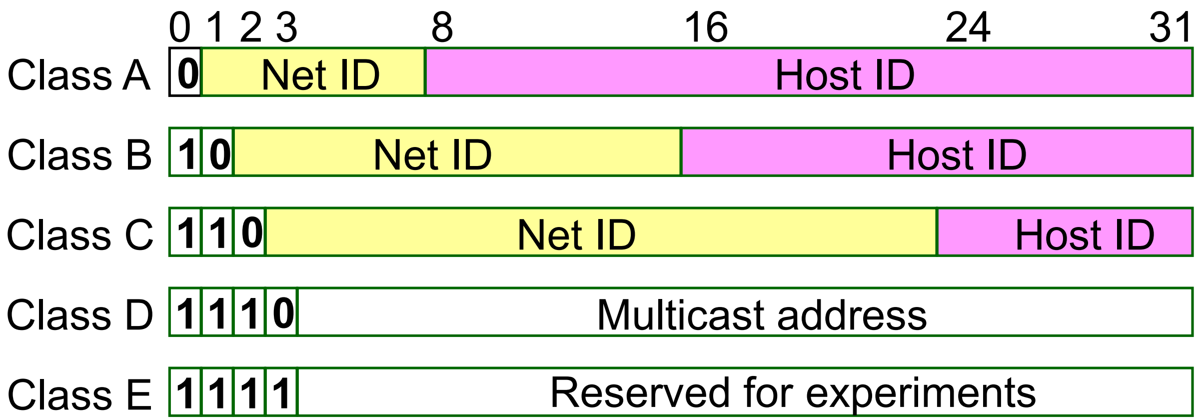
- `htonl`: **convert** `long int` **from host to network byte order**
- `htons`: **convert** `short int` **from host to network byte order**
- `ntohl`: **convert** `long int` **from network to host byte order**
- `ntohs`: **convert** `short int` **from network to host byte order**

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`
- **Functions for converting between binary IP addresses and dotted decimal strings:**
  - `inet_pton`**: converts a dotted decimal string to an IP address in network byte order**
  - `inet_ntop`**: converts an IP address in network by order to its corresponding dotted decimal string**
  - **"`n`" denotes network representation, "`p`" denotes presentation representation**

IP Address Structure

IP (V4) Address space divided into classes:



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

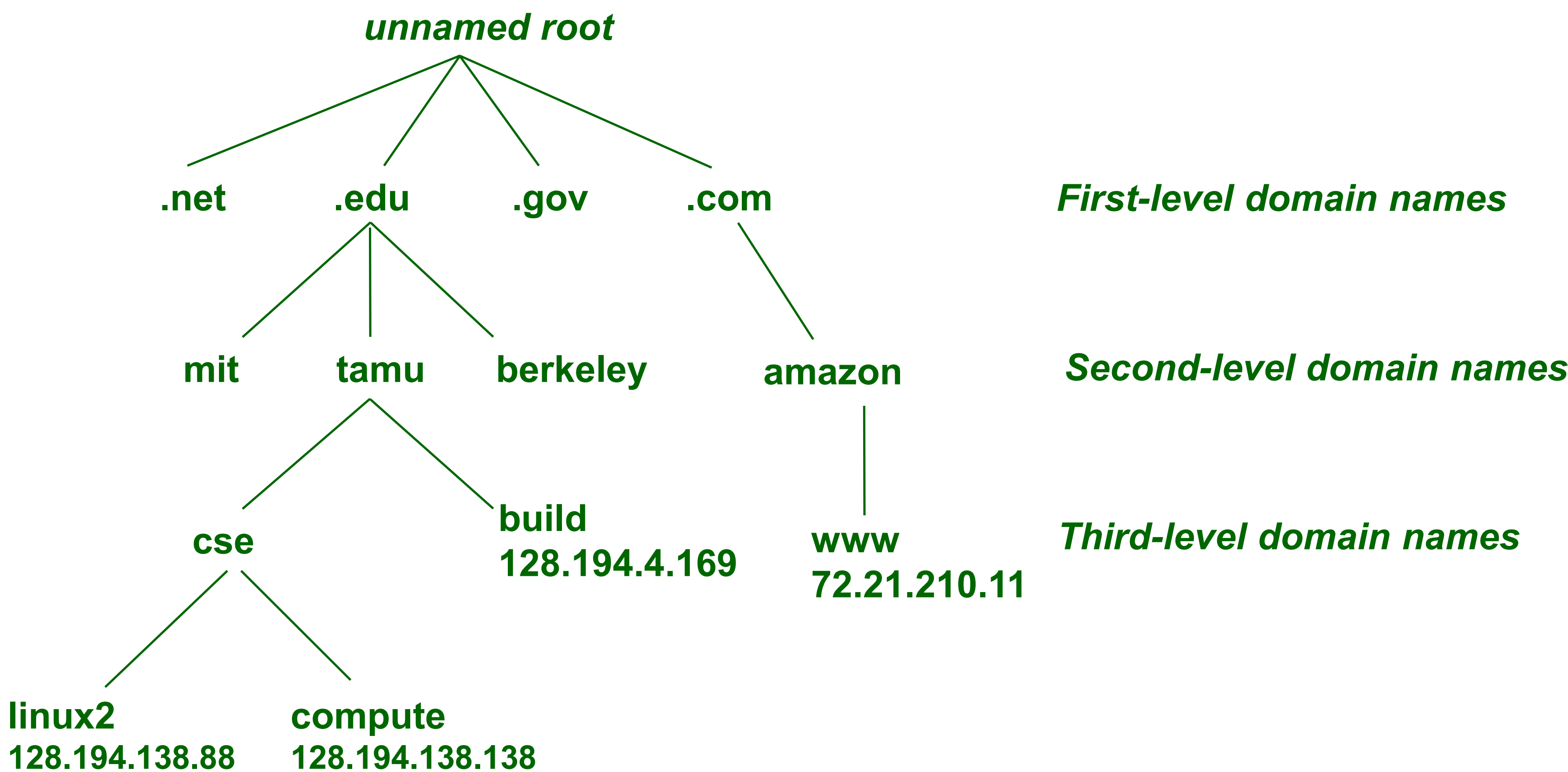
Loop-back address: 127.0.0.1

Unrouted (private) IP addresses:

- **10.0.0.0/8, 172.16.0.0/12, 192.168.0.0/16**

Dynamic IP addresses (DHCP)

Internet Domain Names



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 addrinfo structures:**

```
struct addrinfo {
    int             ai_flags;     /* flags for getaddrinfo */
    int             ai_family;    /* address type (AF_INET or AF_INET6) */
    int             ai_socktype;  /* the socket type */
    int             ai_protocol;  /* the type of protocol */
    size_t          ai_addrlen;   /* length of ai_addr */
    struct sockaddr   *ai_addr;      /* pointer to a sockaddr struct */
    char            *ai_canonname;/* the canonical name */
    struct addrinfo *ai_next; /* pointer to the next addrinfo struct */
};
```

Functions for retrieving host entries from DNS:

- **getaddrinfo: query DNS using domain name or IP**
- **getnameinfo: query DNS using sockaddr struct**

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 domain name maps to one IP address**
- **Multiple domain names mapped to the same IP address**
- **Multiple domain names mapped to multiple IP addresses**
- **Some valid domain names don't map to any IP address**

Querying DNS

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

- **Lots of web interfaces (google "domain information groper")**

```
unix> dig +short linux2.cse.tamu.edu
128.194.138.88
unix> dig +short -x 128.194.138.85
chevron.cs.tamu.edu.
unix> dig +short www.google.com
142.250.114.104
142.250.114.99
142.250.114.106
142.250.114.147
142.250.114.105
142.250.114.103
```

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 and port pair

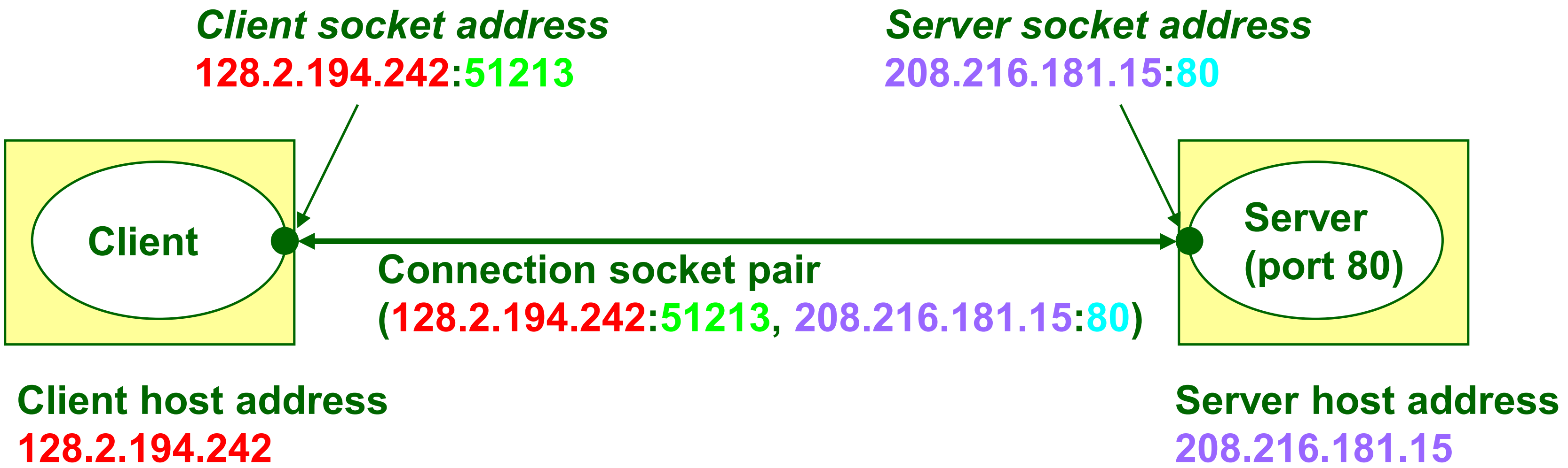
A port is a 16-bit integer that identifies a process:

- 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:cliport, servaddr:servport)

Putting it all Together: Anatomy of an Internet Connection



Prerequisites for an Internet Connection

- There must be a network path between the Client and the Server
  - For instance, there is a path between your cell phone and your computer residing in the same WiFi network
  - A path between your desktop and google.com
- **Firewalls** could artificially **block** network paths
  - Path between off-campus computer and build.tamu.edu is blocked by system admins

Testing for Network Paths

ping command

- Tests if you can reach another host
- Example 1: From off-campus (w/o VPN)

```
osboxes@osboxes:~$ ping www.google.com
PING www.google.com (172.217.1.132) 56(84) bytes of data.
64 bytes from atl14s07-in-f132.1e100.net (172.217.1.132): icmp_seq=1 ttl=55 time=13.8 ms
64 bytes from atl14s07-in-f132.1e100.net (172.217.1.132): icmp_seq=2 ttl=55 time=14.9 ms
64 bytes from atl14s07-in-f132.1e100.net (172.217.1.132): icmp_seq=3 ttl=55 time=13.3 ms
64 bytes from atl14s07-in-f132.1e100.net (172.217.1.132): icmp_seq=4 ttl=55 time=13.5 ms
^C
--- www.google.com ping statistics ---
4 packets transmitted, 4 received, 0% packet loss, time 3009ms
rtt min/avg/max/mdev = 13.296/13.863/14.858/0.599 ms
osboxes@osboxes:~$ ping build.tamu.edu
PING compute.cse.tamu.edu (128.194.138.139) 56(84) bytes of data.
^C
--- compute.cse.tamu.edu ping statistics ---
9 packets transmitted, 0 received, 100% packet loss, time 8195ms

osboxes@osboxes:~$
```

- Example 2: Now with VPN connected

```
osboxes@osboxes:~$ ping build.tamu.edu
PING compute.cse.tamu.edu (128.194.138.139) 56(84) bytes of data.
64 bytes from compute.cs.tamu.edu (128.194.138.139): icmp_seq=1 ttl=59 time=23.2 ms
64 bytes from compute.cs.tamu.edu (128.194.138.139): icmp_seq=2 ttl=59 time=23.7 ms
64 bytes from compute.cs.tamu.edu (128.194.138.139): icmp_seq=3 ttl=59 time=23.0 ms
64 bytes from compute.cs.tamu.edu (128.194.138.139): icmp_seq=4 ttl=59 time=24.4 ms
^C
--- compute.cse.tamu.edu ping statistics ---
4 packets transmitted, 4 received, 0% packet loss, time 3006ms
rtt min/avg/max/mdev = 22.999/23.560/24.391/0.544 ms
```

TCP Connectivity in the Path

telent command

- A built in TCP client, used to check server existence or connection ability
- Tests if you can make a TCP connection to a server port
- <u>Example 1:</u> Connecting to port 80 (HTTP server) of google

```
osboxes@osboxes:~$ telnet www.google.com 80
Trying 172.217.14.164...
Connected to www.google.com.
Escape character is '^]'.
```

- <u>Example 2:</u> Connecting to port 80 of build.tamu

```
osboxes@osboxes:~$ telnet build.tamu.edu 80
Trying 128.194.138.139...
^C
osboxes@osboxes:~$
```

  - Connection not possible because:
    - No service at port 80
    - Even if it had, firewall does not allow

Clients

Examples of client programs

- Web browsers, ftp, telnet, ssh

How does a client find the server?

- The IP address in the server socket address identifies the host (more precisely, an adapter on the host)
- The (well-known) port in the server socket address identifies the service, and thus implicitly identifies the server process that performs that service

Servers

- Servers are long-running processes (daemons)
  - Created at boot-time (typically) by the init process (process 1)
  - Run continuously until the machine is turned off
- Each server waits for requests to arrive on a well-known port associated with a particular service
  - Port 23: telnet server
  - Port 25: mail server
  - Port 80: HTTP server
- A machine that runs a server process is also often referred to as a "server"

Server Examples

Web server (port 80)

- Resource: files/compute cycles (CGI programs)
- Service: retrieves files and runs CGI programs on behalf of the client

FTP server (20, 21)

- Resource: files
- Service: stores and retrieve files

See `/etc/services` for a comprehensive list of the services available on a UNIX machine

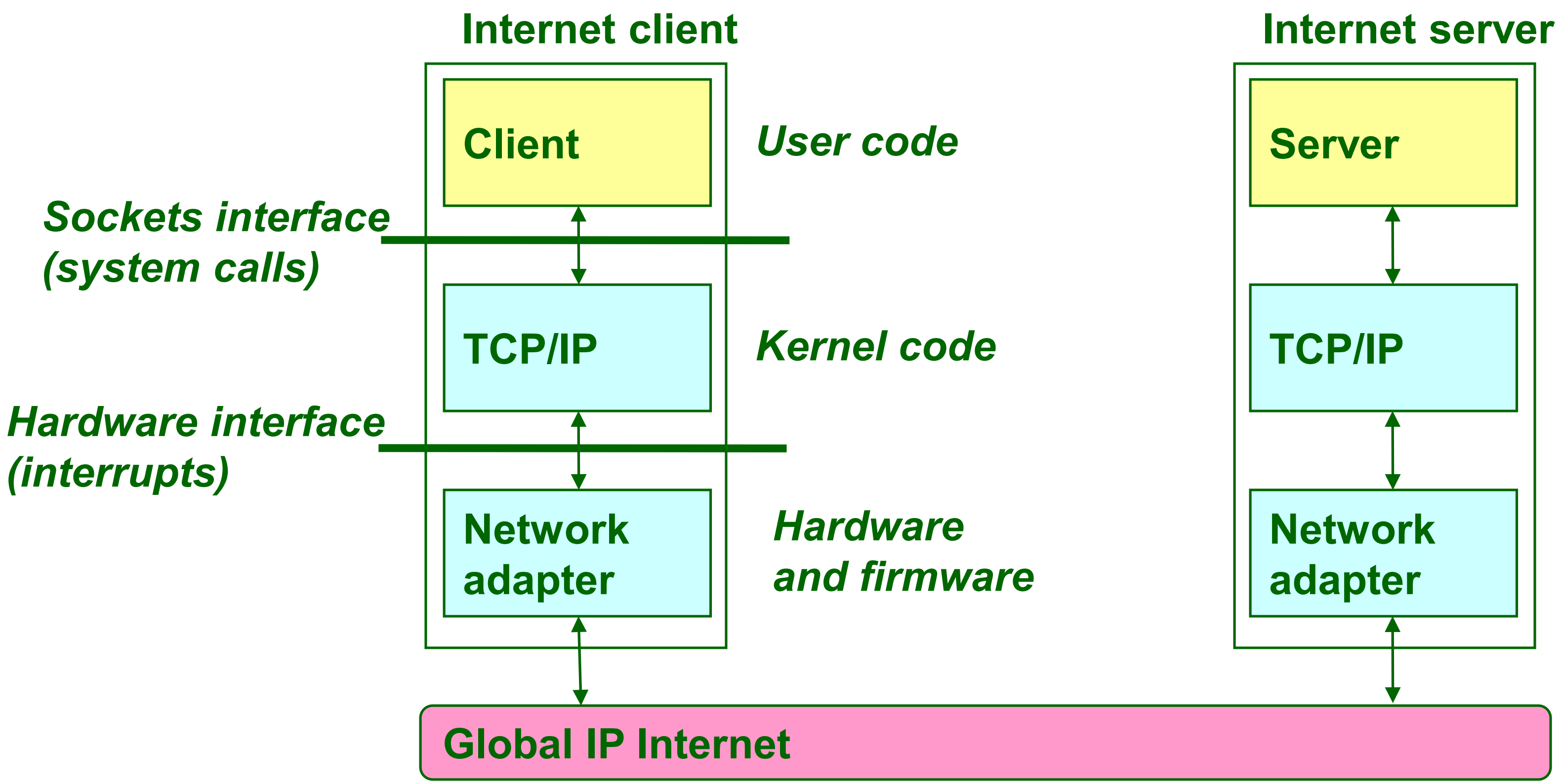
Telnet server (23)

- Resource: terminal
- Service: proxies a terminal on the server machine

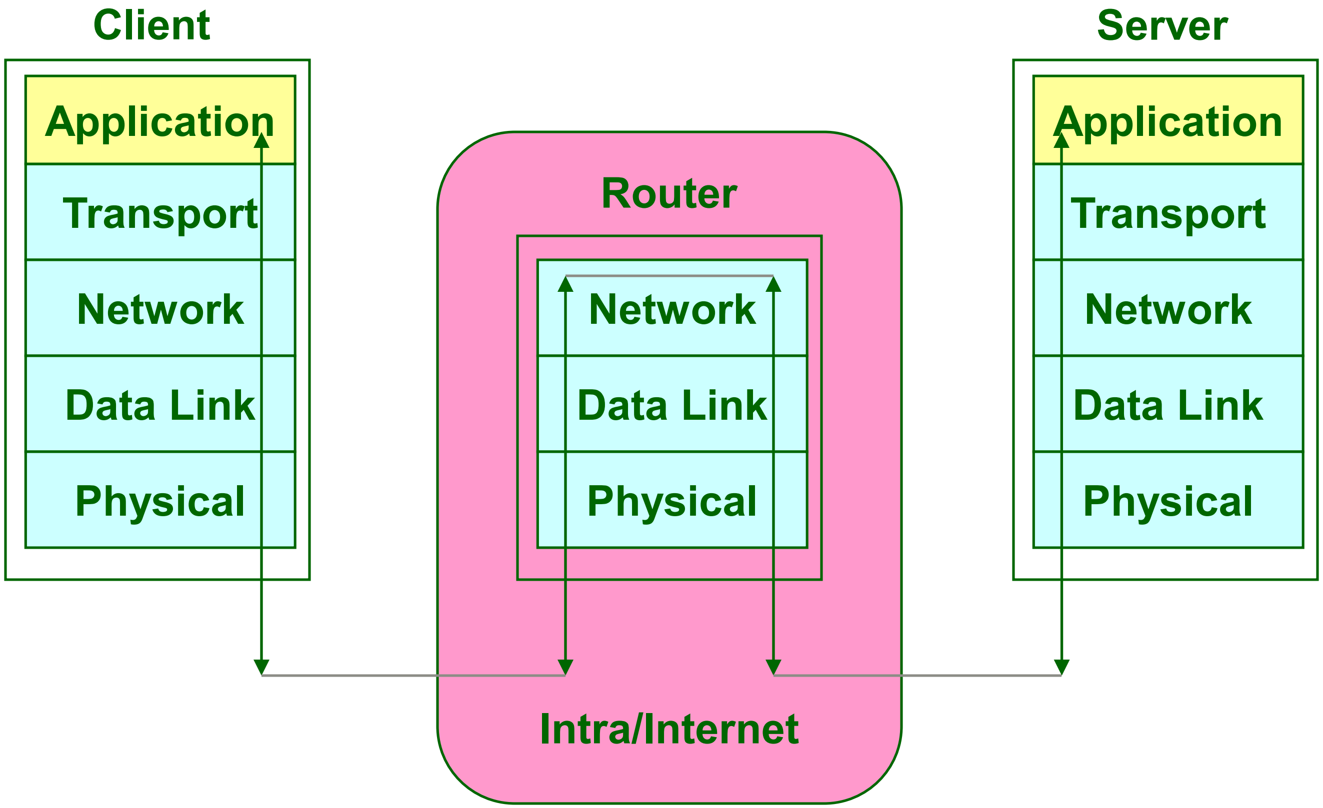
Mail server (25)

- Resource: email “spool” file
- Service: stores mail messages in spool file

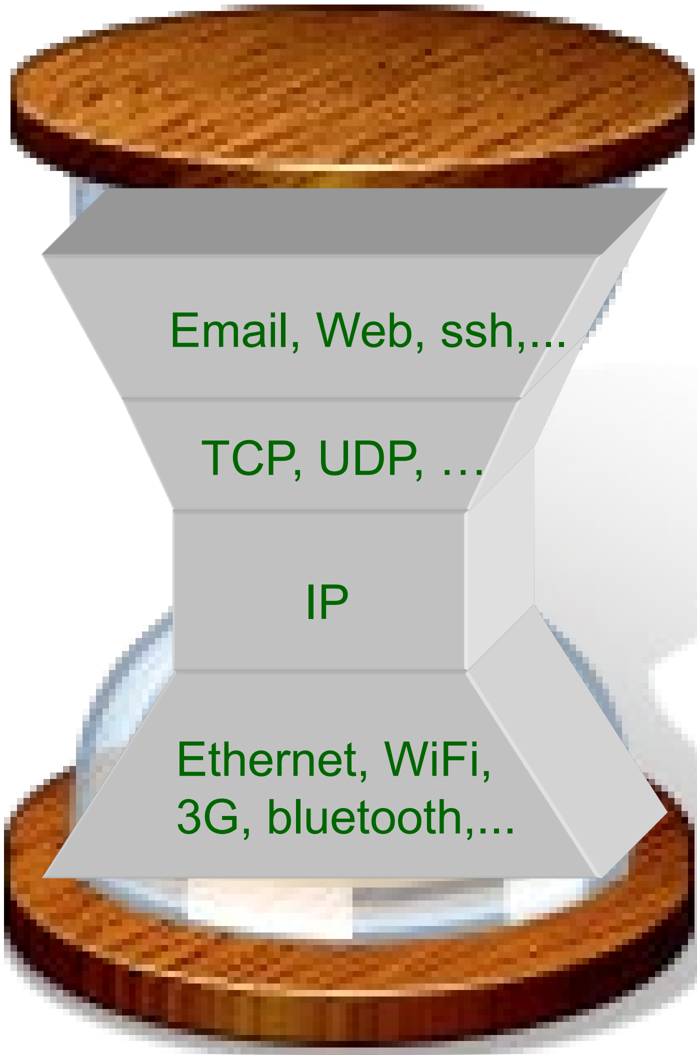
Organization of an Internet Application

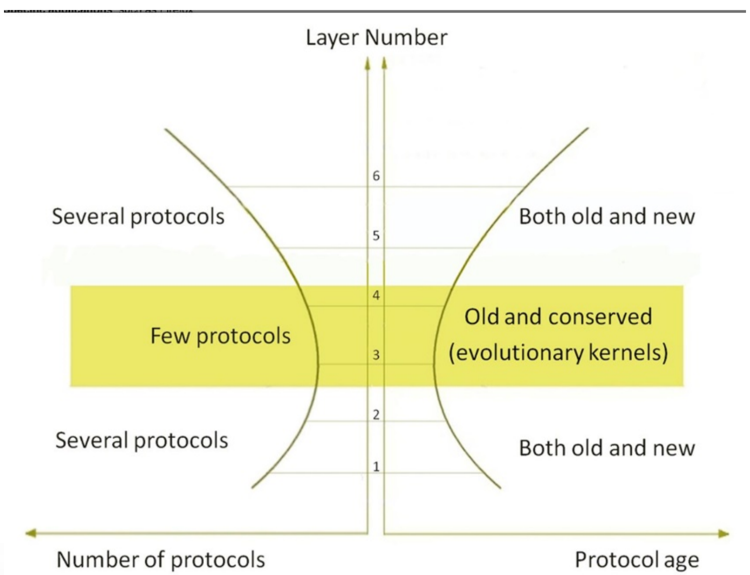


OSI Model (Layers)



Internet Hourglass Architecture





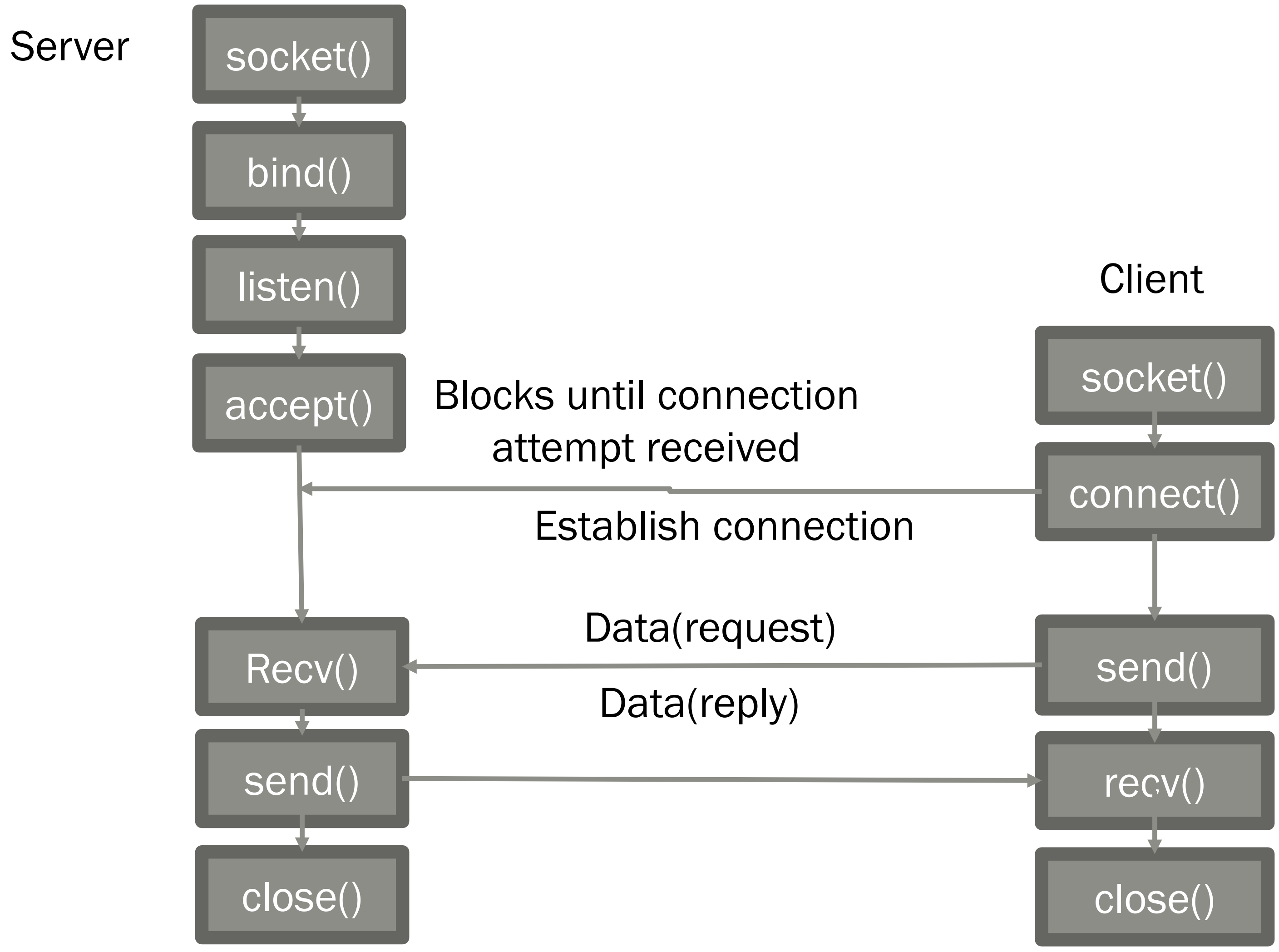
Source: [GATECH Internet Hourglass Architecture]

From top to bottom, the Internet architecture consists of six layers:

1. **Specific applications**, such as Firefox;
2. **Application protocols**, such as Hypertext Transfer Protocol (HTTP);
3. **Transport protocols**, such as Transmission Control Protocol (TCP);
4. **Network protocols**, such as Internet Protocol (IP);
5. **Data-link protocols**, such as Ethernet; and
6. **Physical layer protocols**, such as DSL.

Layers near the top and bottom contain many items, called protocols. The central transport layer contains two protocols and the network layer contains only one, creating an hourglass architectu

A Server-Client Interaction in TCP – POSIX Functions



A Closer Look into POSIX Functions

- `getaddrinfo()`
- `socket()`
- `bind()`
- `listen()`
- `accept()`
- `connect()`
- `write()`, `send()`, `sendto()`
- `read()`, `recv()`, `recvfrom()`
- `close()`

Data Structures

```
/* structure for looking up IP address */
struct addrinfo{
    int     ai_flags;
    int     ai_family; // AF_INET=IPv4,AF_INET6= IPv6
    int     ai_socktype;       // TCP or UDP
    int     ai_protocol;
    socklen_t  ai_addrlen;     // length of ai_addr
    struct sockaddr* ai_addr; // contains IP+PORT
    char*   ai_canonname;      // canonical name
    struct addrinfo* ai_next; // next pointer of result
link list
};
/* data structure for IP details (+PORT) */
struct sockaddr_in{
    short       sin_family;  // IPv4 or IPv6
    unsigned short sin_port; // port number
    struct in_addr sin_addr; // 32 bit IP
    char sin_zero [8];
};
/* just a wrapper for the numeric IP */
struct in_addr{
    unsigned long s_addr;
};
```

getaddrinfo() – Looking Up IP address from name

- **The first step to locate a server by the client**
- **Converts easy-to-remember DNS names (e.g., linux.cs.tamu.edu) into machine-usable IP address**
- **Queries DNS servers (a collection of mappings)**

  ```
  int getaddrinfo(char* name, char* port, struct addrinfo* hints, struct addrinfo** result);
  ```

  `name` = name of the host

  `port` = the port where the service (e.g., http, your data server in MP6) is running

  `hints` = provides some initial hint (IPv4/IPv6, TCP/UDP etc.)

  result = linked list of looked up addresses
- **Example:**

  ```
  getaddrinfo("www.example.com", "3490", &hints, &res);
  ```

getaddrinfo() - Detailed

```
int status;
struct addrinfo hints;
struct addrinfo *servinfo;  // will point to the results

//preparing hints data structure
memset(&hints, 0, sizeof hints); // make sure the struct is empty
hints.ai_family = AF_UNSPEC;     // don't care IPv4 or IPv6
hints.ai_socktype = SOCK_STREAM; // TCP stream sockets

// look up the IP address from the name: "www.example.com"
status = getaddrinfo("www.example.net", "3490", &hints, &servinfo);

for(p = res;p != NULL; p = p->ai_next) {
      void *addr;
      char *ipver;
      // get the pointer to the address itself,
      // different fields in IPv4 and IPv6:
      if (p->ai_family == AF_INET) { // IPv4
            struct sockaddr_in *ipv4 = (struct sockaddr_in *)p->ai_addr;
            addr = &(ipv4->sin_addr);
            ipver = "IPv4";
      } else { // IPv6
            struct sockaddr_in6 *ipv6 = (struct sockaddr_in6 *)p->ai_addr;
            addr = &(ipv6->sin6_addr);
            ipver = "IPv6";
      }
      // convert the IP to a string and print it:
      inet_ntop(p->ai_family, addr, ipstr, sizeof ipstr);
      printf("  %s: %s\n", ipver, ipstr);
}
```

socket() – A Connection End Point

- **Creates a communication end-point for a network connection**

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

  domain = PF_INET (IPv4) / PF_INET6 (IPv6)

  type = SOCK_STREAM (TCP) / SOCK_DGRAM (UDP)

  protocol = 0
- **Example:**

```
s = socket (PF_INET, SOCK_STREAM, 0)
```

will create a TCP socket

- **The above call returns -1 on failure**

connect() – Client Attempting Server Connection

- **This is called by the client to attempt a connection with the server**
- **Blocks until the server accepts it**

  `int connect(int sockfd, struct sockaddr* server, socketlen_t server_len)`

Sockfd: socket variable prepared beforehand

server = address of the server (returned by getaddrinfo)

- **Example:**

```
getaddrinfo("www.example.com", "3490", &hints, &res); // lookup
// make a socket:
sockfd = socket(res->ai_family, res->ai_socktype, res->ai_protocol);
// connect to server. Once successful, the socket becomes ready as the endpoint
connect(sockfd, res->ai_addr, res->ai_addrlen);
```

close() – Close a Session

- **Called by both the client and the server**
- **Signals end of a communication**
- **Internally, frees resources associated with a connection**
  - **Important for busy servers, also for PA6**

    `int close(int sock)`
- **Example:**

```
close (sock)
```

bind() – Server Attaching to a Port

- **A server process calls this to associate its socket to a given port**
- **Port number is used by the kernel to forward an incoming packet to a certain process (its socket)**

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

- **Example:**

```
getaddrinfo(NULL, "3490", &hints, &res); // lookup
// make a socket:
sockfd = socket(res->ai_family, res->ai_socktype, res->ai_protocol);
// bind it to the port we passed in to getaddrinfo():
bind(sockfd, res->ai_addr, res->ai_addrlen);
```

listen() – Setting up Server

- **This is a prerequisite before a connection is accepted**
- **Incoming connections wait in a queue before accepted, listen () sets the size of that queue**

  `int listen(int sockfd, int backlog)`

- **Example:**

```
listen (sockfd, 20); // 20 is good for most purposes, at least
for your data server in MP6
```

accept() – Server Accepting Client Connection

- **This is called by the server to accept a new client connection**

  `int accept(int sockfd, struct sockaddr* client, socketlen_t client_len)`

`sockfd = socket`

`client = will hold the client address details`

`client_len = address length`

- **Example:**

```
struct sockaddr client;
accept (sockfd, &client, sizeof (client));
```

send()/recv() – Finally Data

- **Called by both client and server to exchange data**
- **Blocks until the server accepts it**

```
int send(int sock, void* msg, size_t len, int flags)
int recv(int sock, void* msg, size_t len, int flags)
Msg = buffer pointer to send/receive data from/to
Len = sender: length of the message,
      receiver: buffer capacity (to avoid overflow)
```

- **Example:**

```
char *send_msg = "a sample message";
int sent_bytes = send (sockfd, send_msg, strlen (send_msg)+1, 0);

char recv_buffer [1024];
int recv_len = recv (sockfd, recv_buffer, 1024, 0);
```