

Network Programming: Part I

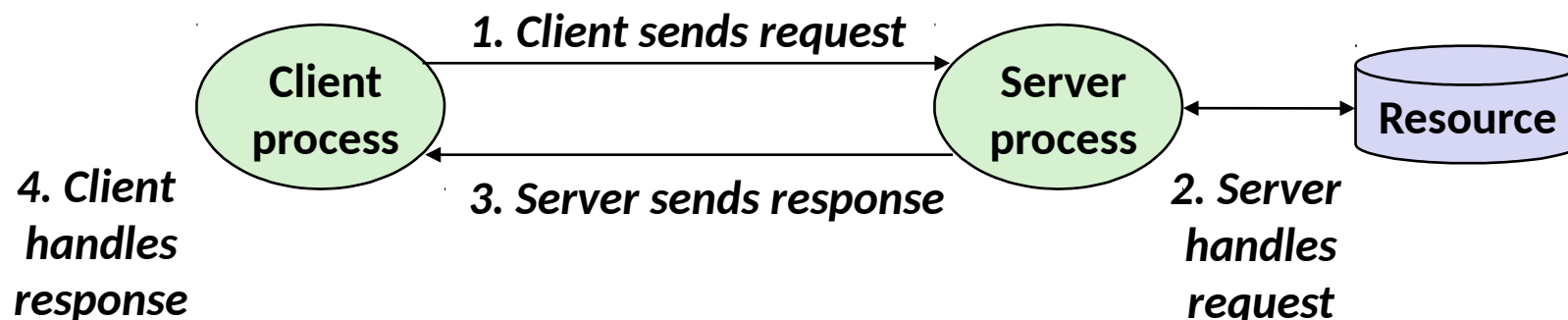
15-213: Introduction to Computer Systems
“21st” Lecture, July 17, 2018

Instructor:

Sol Boucher

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)

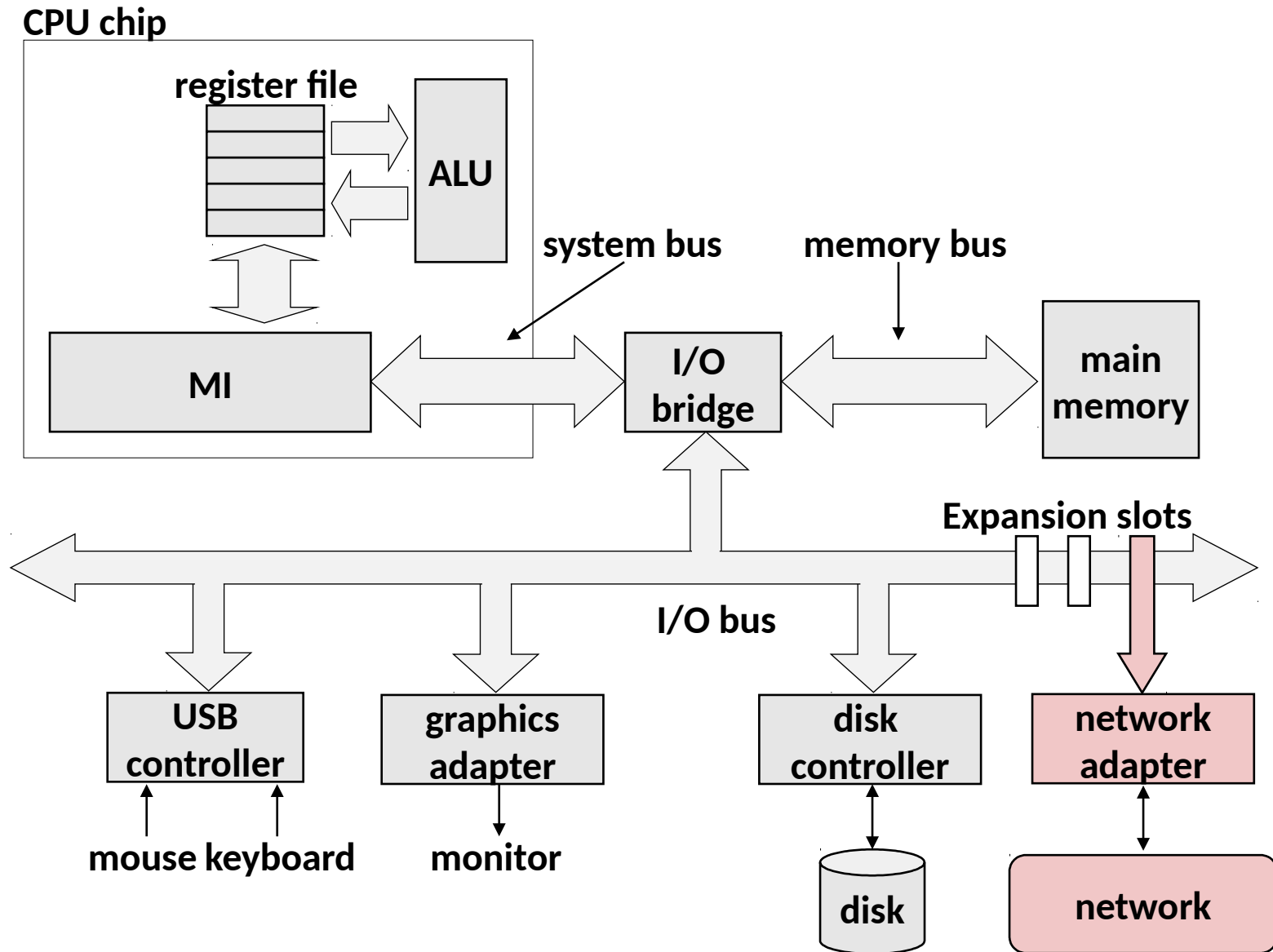
Computer Networks

- 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

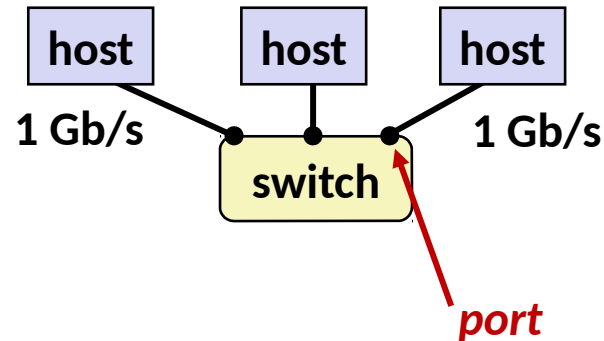
- An ***internetwork*** (***internet***) is an interconnected set of networks
 - The Global IP Internet (uppercase “I”) is the most famous example of an internet (lowercase “i”)

- Let’s see how an internet is built from the ground up

Hardware Organization of a Network Host

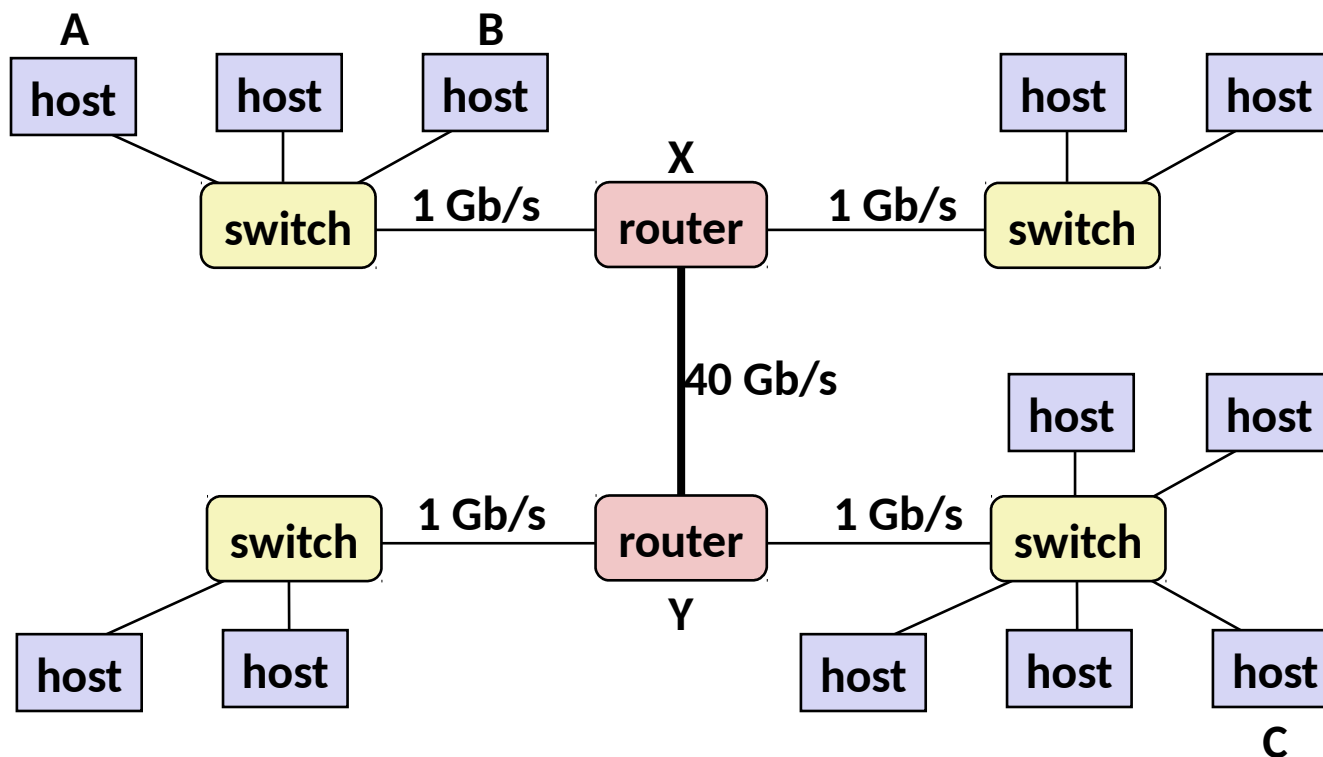


Lowest Level: Ethernet Segment



- 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

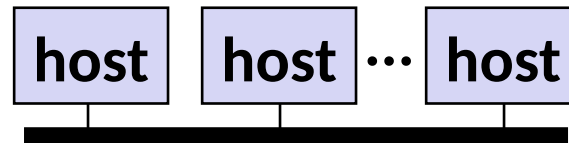
Next Level: Bridged Ethernet Segment



- Spans building or campus
- Specialized computers called *routers* link network segments

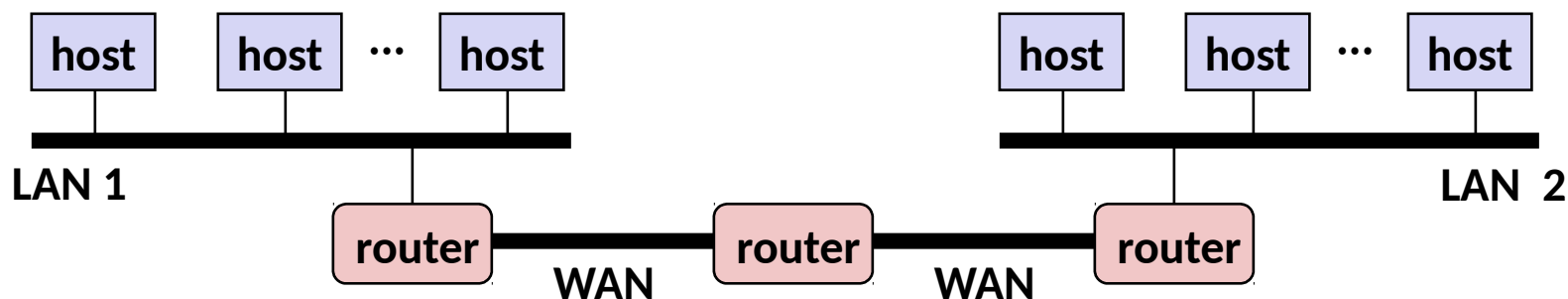
Conceptual View of LANs

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



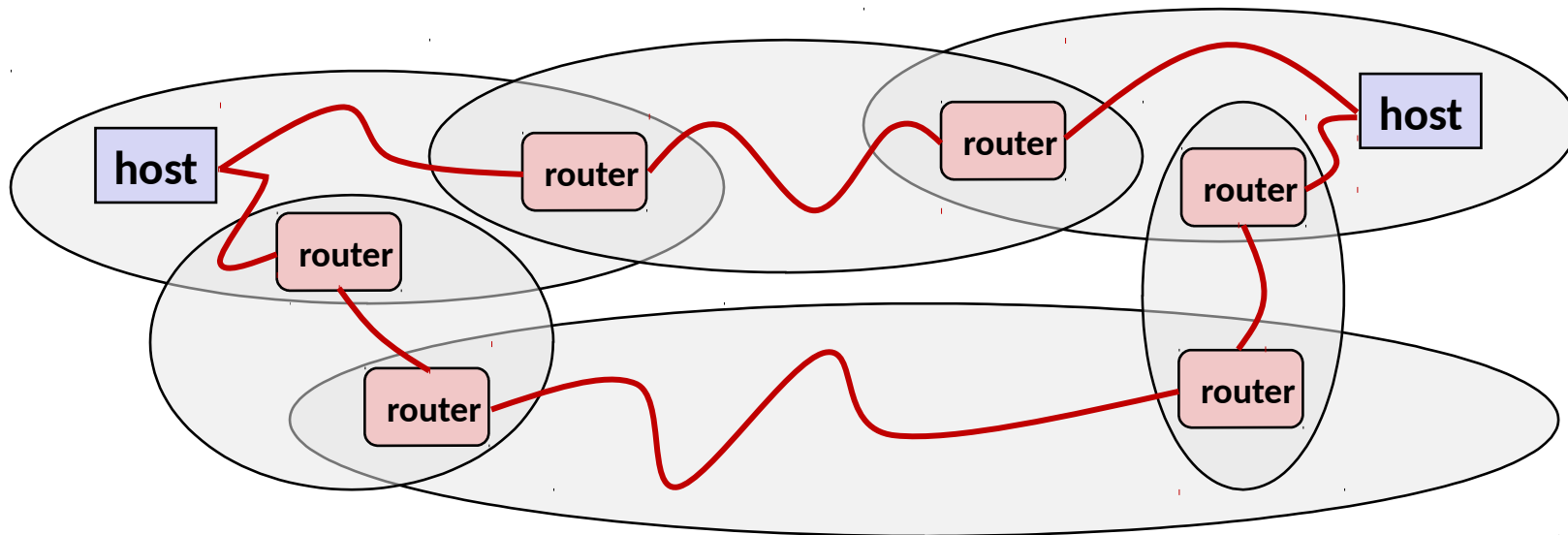
Next Level: internets

- 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, ...)*

Logical Structure of an internet



- **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?

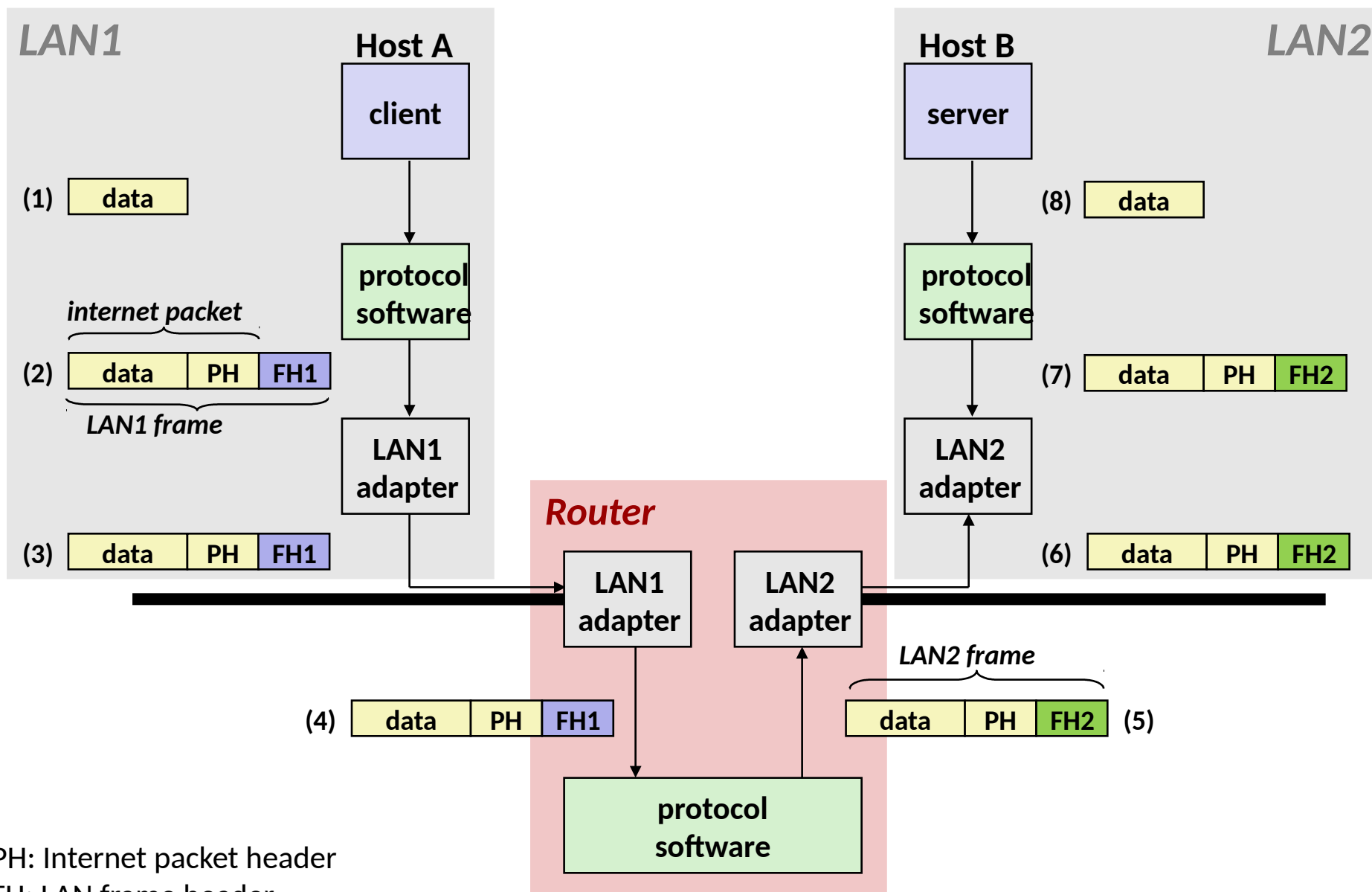
■ Provides a *naming scheme*

- 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



Other Issues

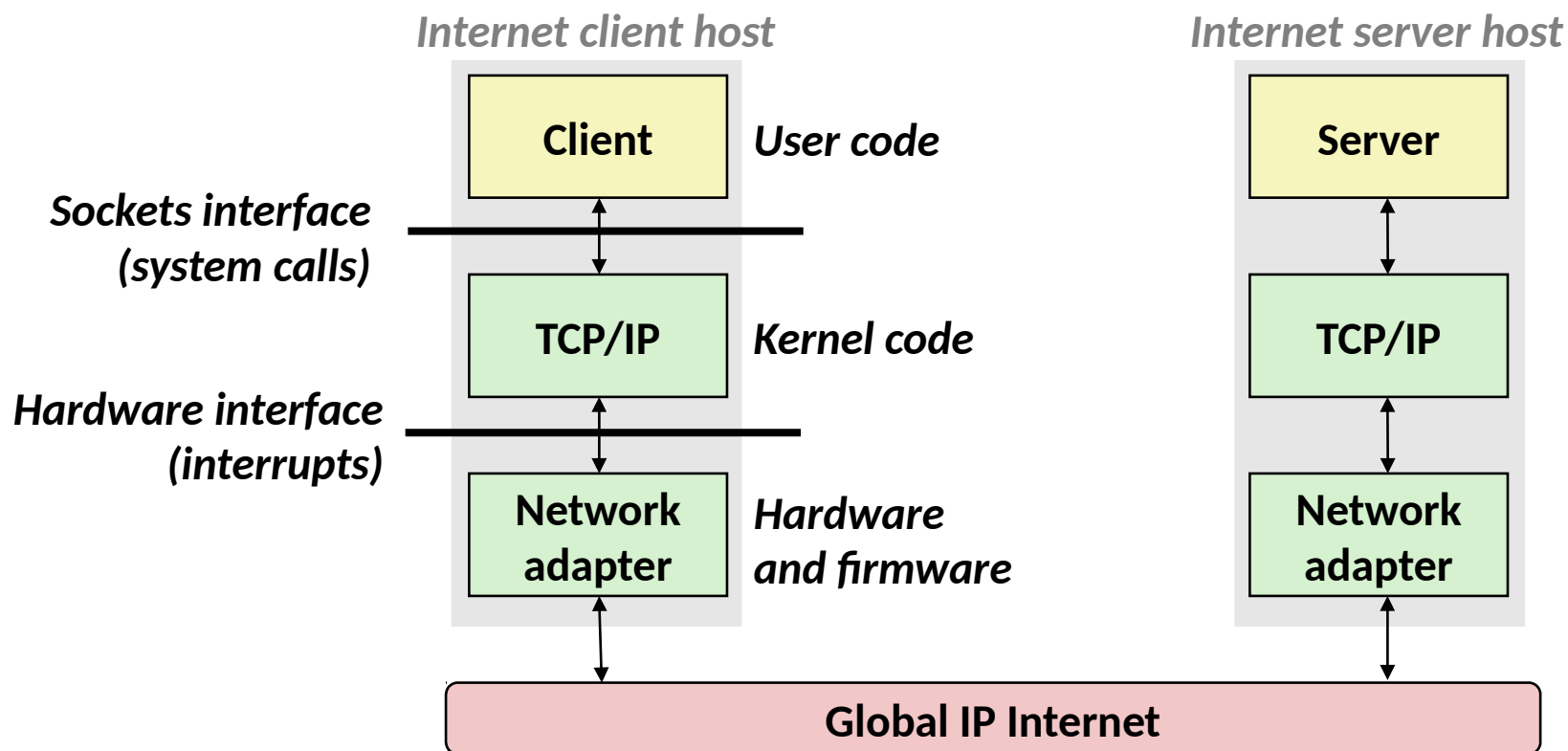
- **We are glossing over a number of important questions:**
 - What if different networks have different maximum frame sizes? (segmentation)
 - How do routers know where to forward frames?
 - How are routers informed when the network topology changes?
 - What if packets get lost?

- **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



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

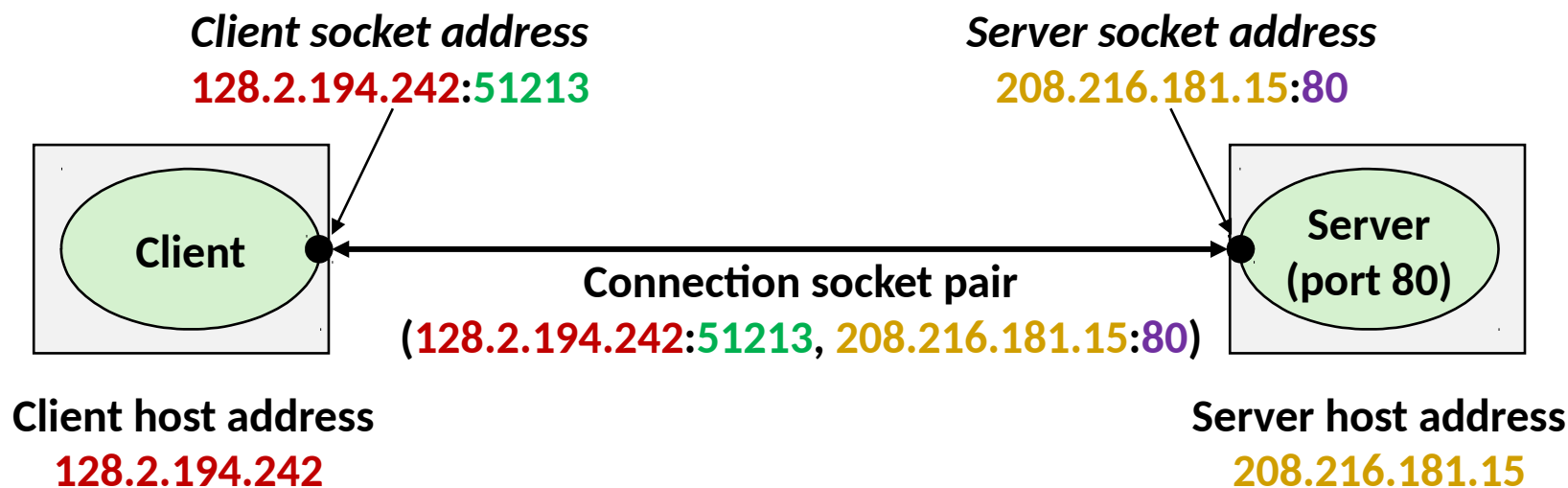
- Clients and servers communicate by sending streams of bytes over **connections**. Each connection is:
 - *Point-to-point*: connects a pair of processes.
 - *Full-duplex*: data can flow in both directions at the same time,
 - *Reliable*: stream of bytes sent by the source is eventually received by the destination in the same order it was sent.
- A **socket** is an endpoint of a connection
 - *Socket address* is an **IPaddress: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

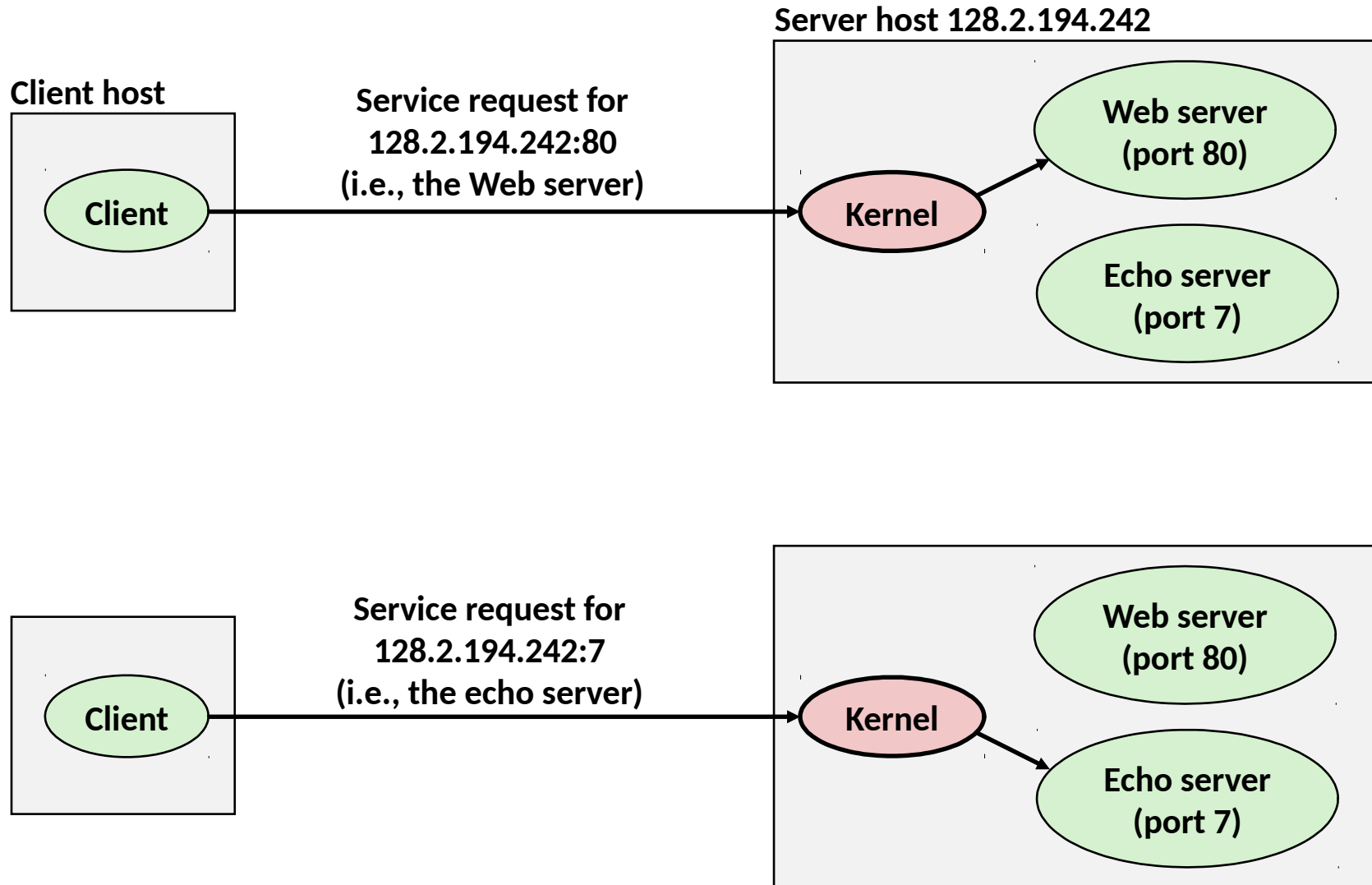
- A connection is uniquely identified by the socket addresses of its endpoints (*socket pair*)
 - (cliaddr:cliport, servaddr:servport)



51213 is an ephemeral port allocated by the kernel

80 is a well-known port associated with Web servers

Using Ports to Identify Services



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

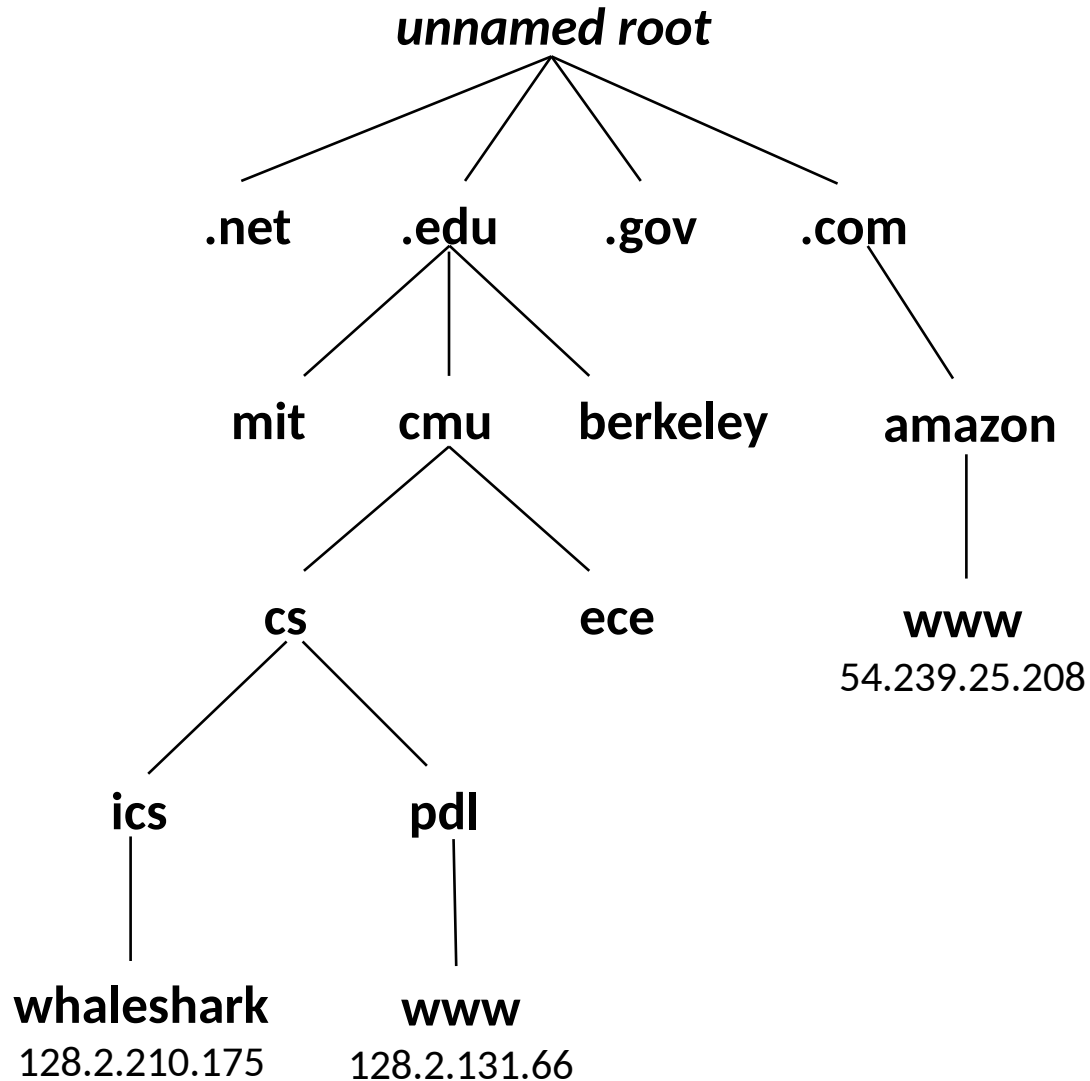
- 32-bit IP addresses are stored in an *IP address struct*
 - IP addresses are always stored in memory in *network byte order* (big-endian byte order)
 - True in general for any integer transferred in a packet header from one machine to another.
 - E.g., the port number used to identify an Internet connection.

```
/* 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



First-level domain names

Second-level domain names

Third-level 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 *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
```

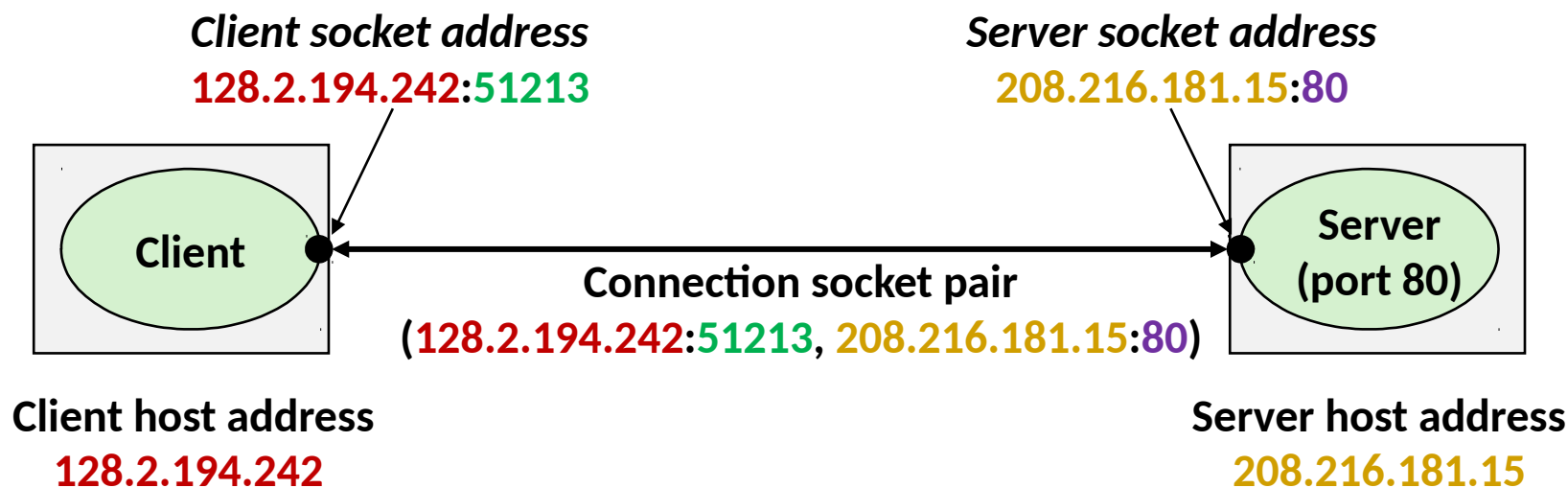
```
linux> nslookup www.twitter.com
Address: 104.244.42.129
Address: 104.244.42.65
Address: 104.244.42.193
Address: 104.244.42.1
```

- 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

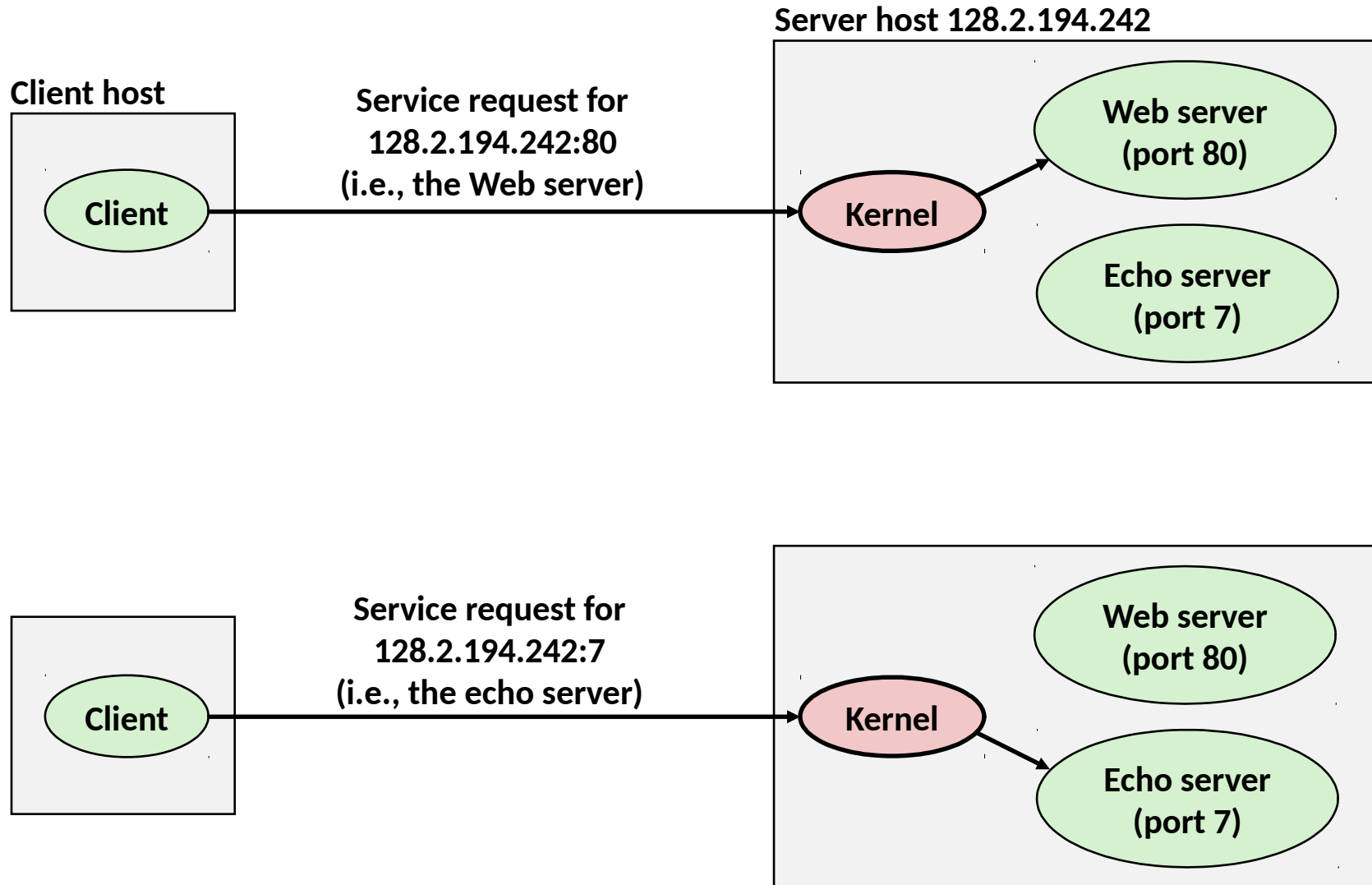
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Using Ports to Identify Services



Sockets Interface

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- 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.

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      (A)
This line is being echoed                                     (B)
This line is being echoed
This one is, too                                           (C)
This one is, too
^D
bambooshark: ./echoclient whaleshark.ics.cs.cmu.edu 6616      (D)
This one is a new connection                               (E)
This one is a new connection
^D

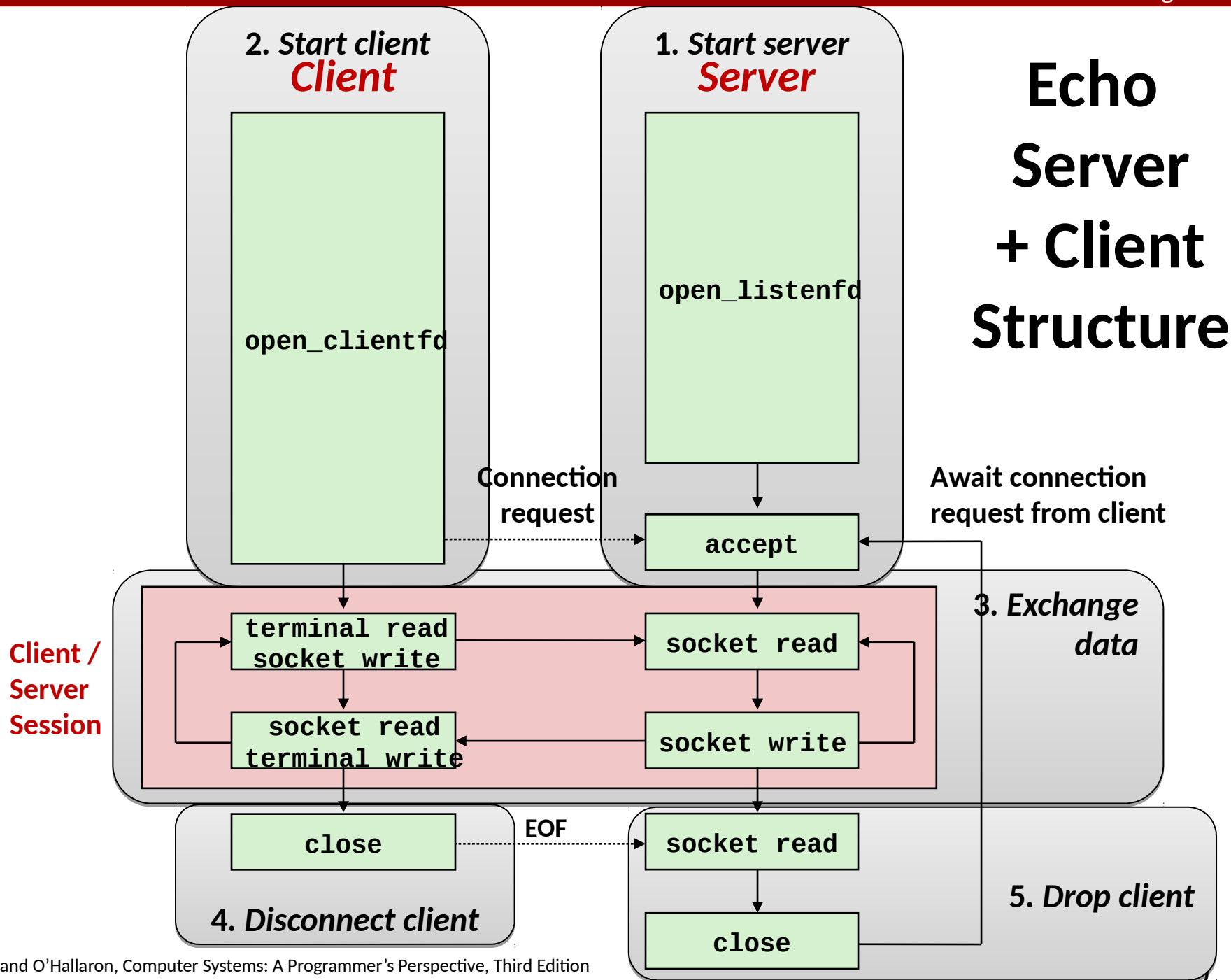
```

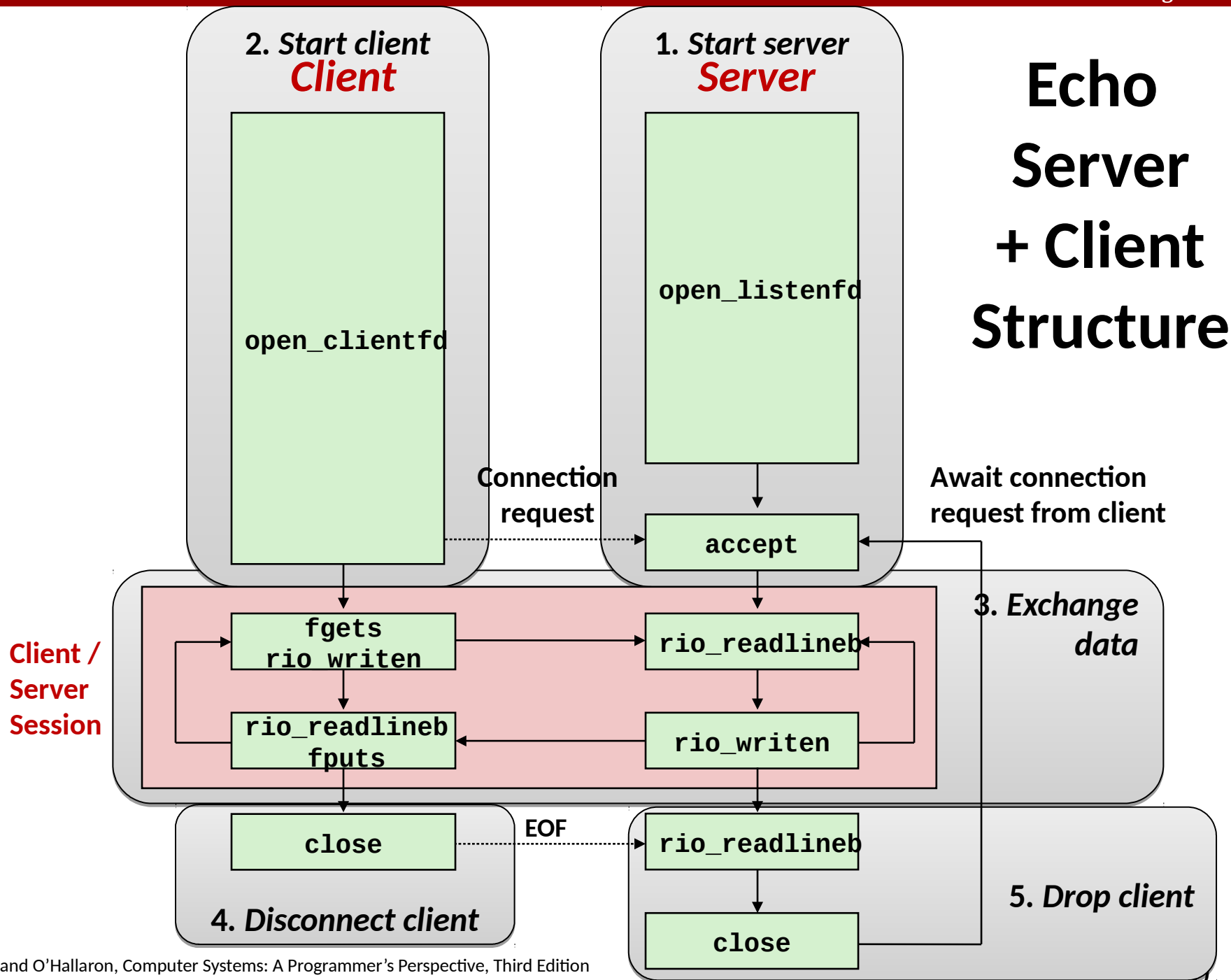
Server

```

whaleshark: ./echoserveri 6616
Connected to (BAMBOOSHARK.ICS.CS.CMU.EDU, 33707)          (A)
server received 26 bytes                                    (B)
server received 17 bytes                                    (C)
Connected to (BAMBOOSHARK.ICS.CS.CMU.EDU, 33708)          (D)
server received 29 bytes                                    (E)

```





Echo Client: Main Routine

```
#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);
}
```

echoclient.c

Iterative Echo Server: Main Routine

```
#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);
}
```

echoserveri.c

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)`

```
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);
    }
}
```

echo.c

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;

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

sa_family



Family Specific

Socket Address Structures

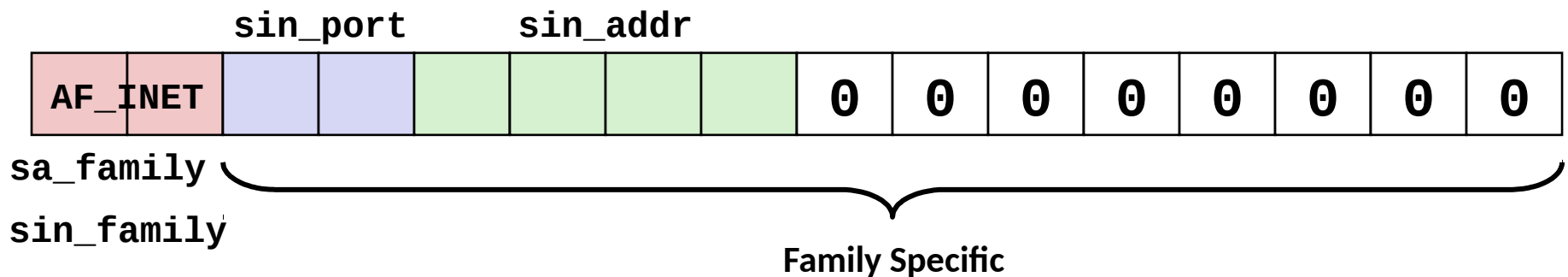
■ Internet (IPv4) specific socket address:

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

```

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) */
};

```



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`

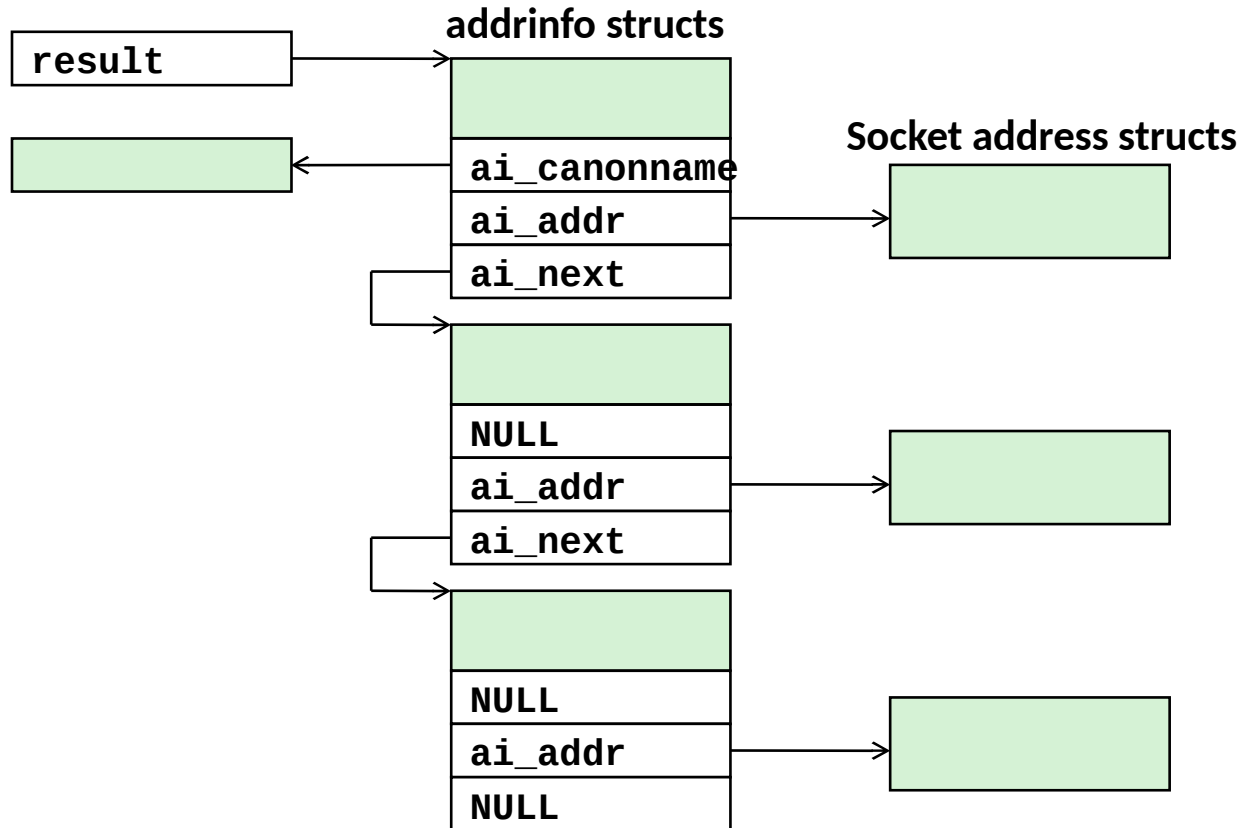
```
int getaddrinfo(const char *host,          /* Hostname or address */
               const char *service,      /* Port or service name */
               const struct addrinfo *hints, /* Input parameters */
               struct addrinfo **result); /* Output linked list */

void freeaddrinfo(struct addrinfo *result); /* Free linked list */

const char *gai_strerror(int errcode);    /* Return error msg */
```

- 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.

Linked List Returned by `getaddrinfo`



- **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

```
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.

```
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

```
#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)

```
/* 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);
}
```

hostinfo.c

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
```

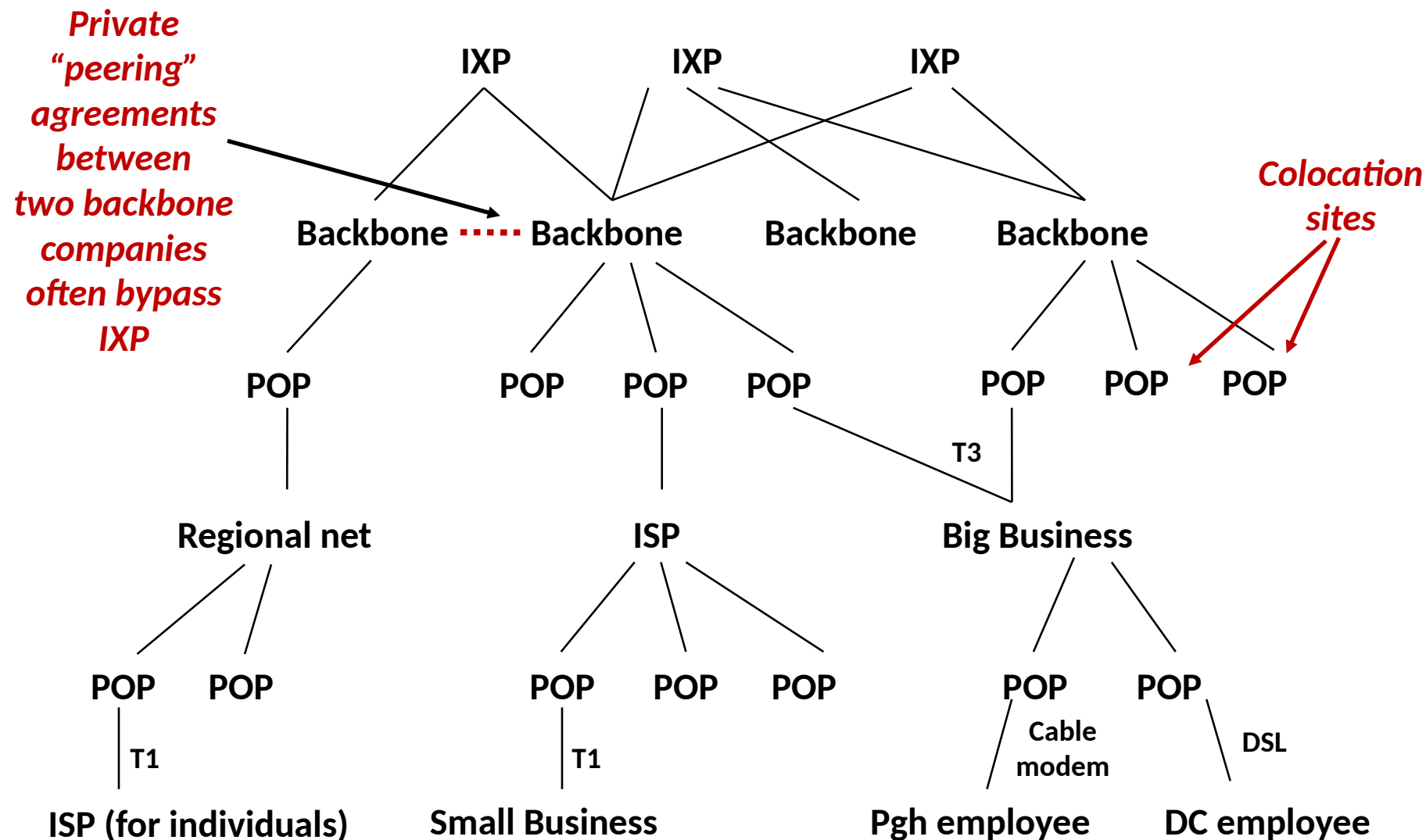
Next time

- Using `getaddrinfo` for host and service conversion
- Writing clients and servers
- Writing Web servers!

Basic Internet Components

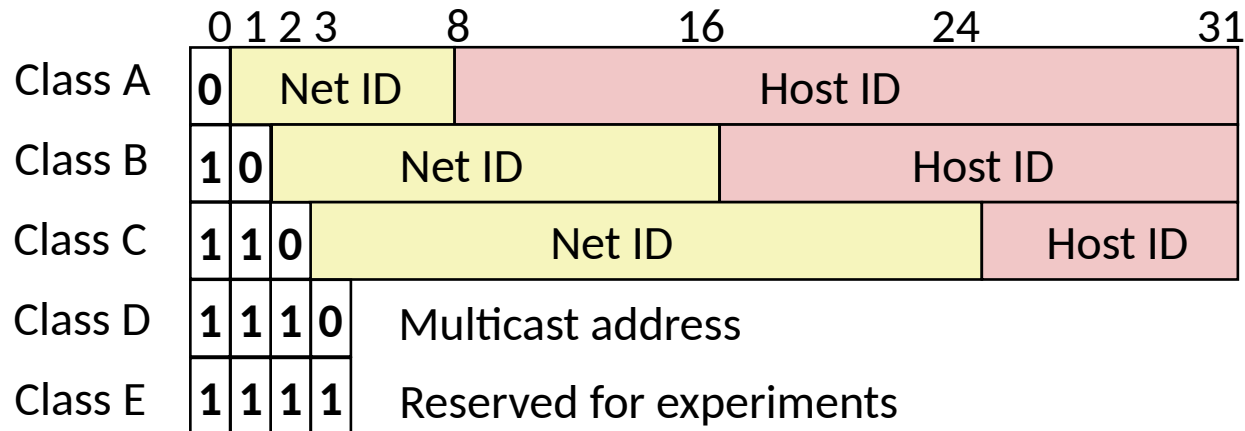
- **Internet backbone:**
 - collection of routers (nationwide or worldwide) connected by high-speed point-to-point networks
- **Internet Exchange Points (IXP):**
 - router that connects multiple backbones (often referred to as peers)
 - Also called Network Access Points (NAP)
- **Regional networks:**
 - 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



IP Address Structure

- IP (V4) Address space divided into classes:



- 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

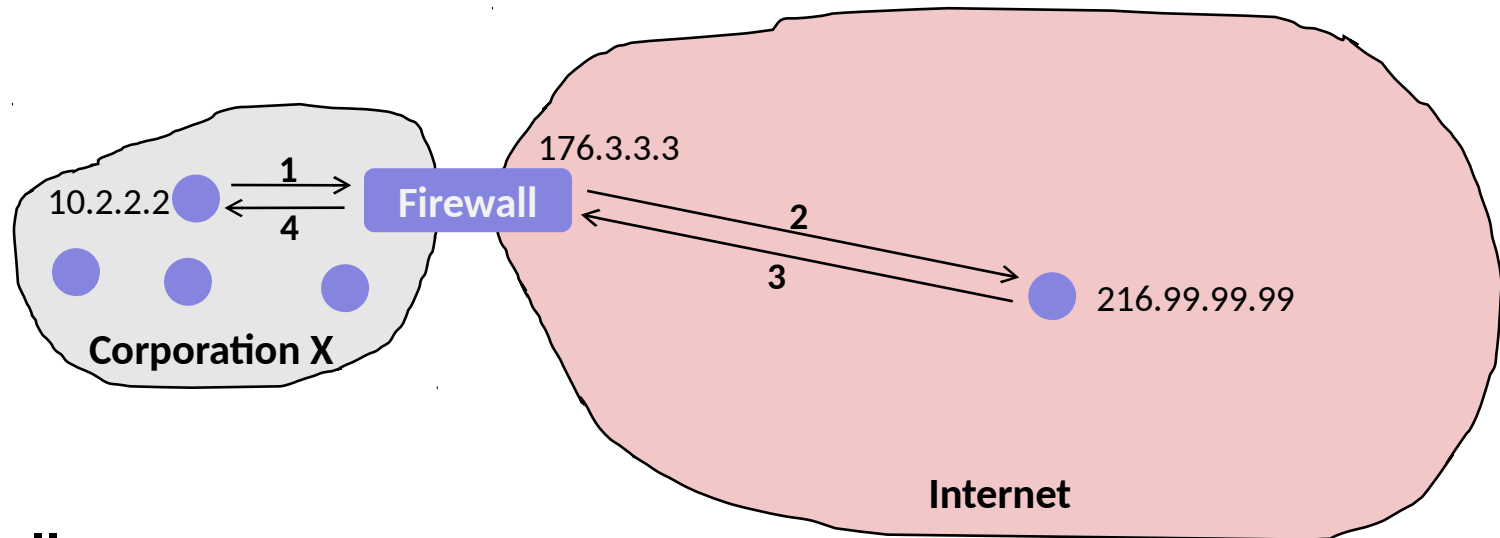
■ Dynamic address assignment

- 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