

Network Programming: Part I

CSE4100: System Programming

Youngjae Kim (PhD)

<https://sites.google.com/site/youkim/home>

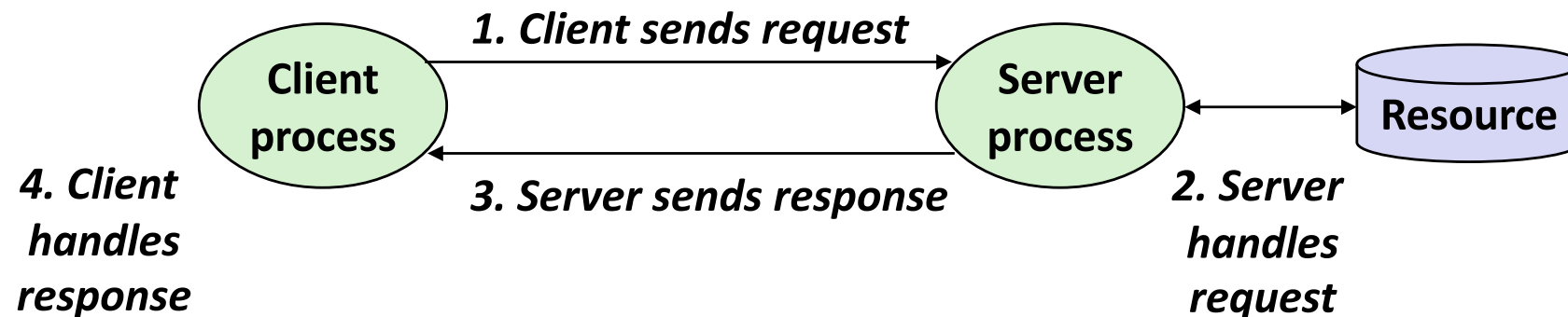
Distributed Computing and Operating Systems Laboratory (DISCOS)

<https://discos.sogang.ac.kr>

Office: R911, E-mail: youkim@sogang.ac.kr

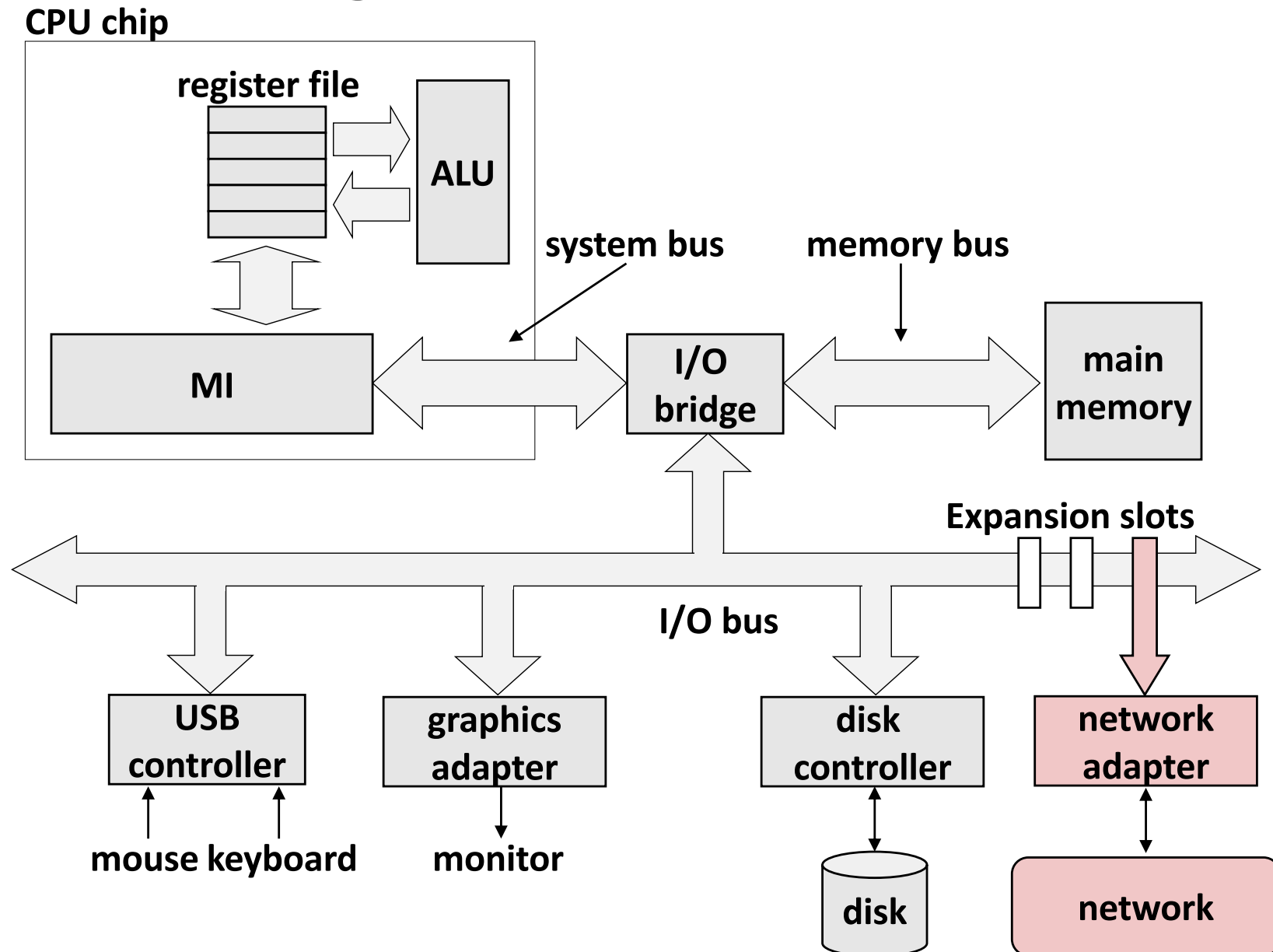
A Client-Server Transaction

- 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)

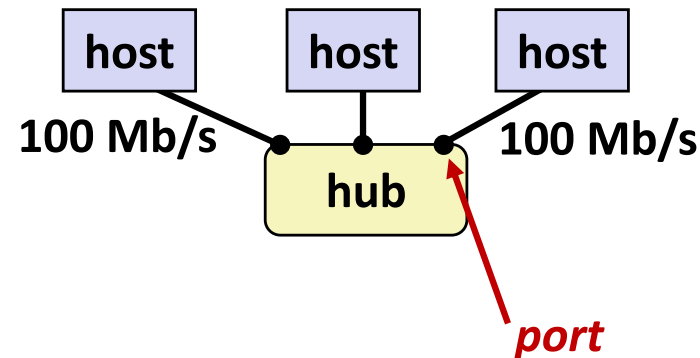
Hardware Organization of a Network Host



Computer Networks

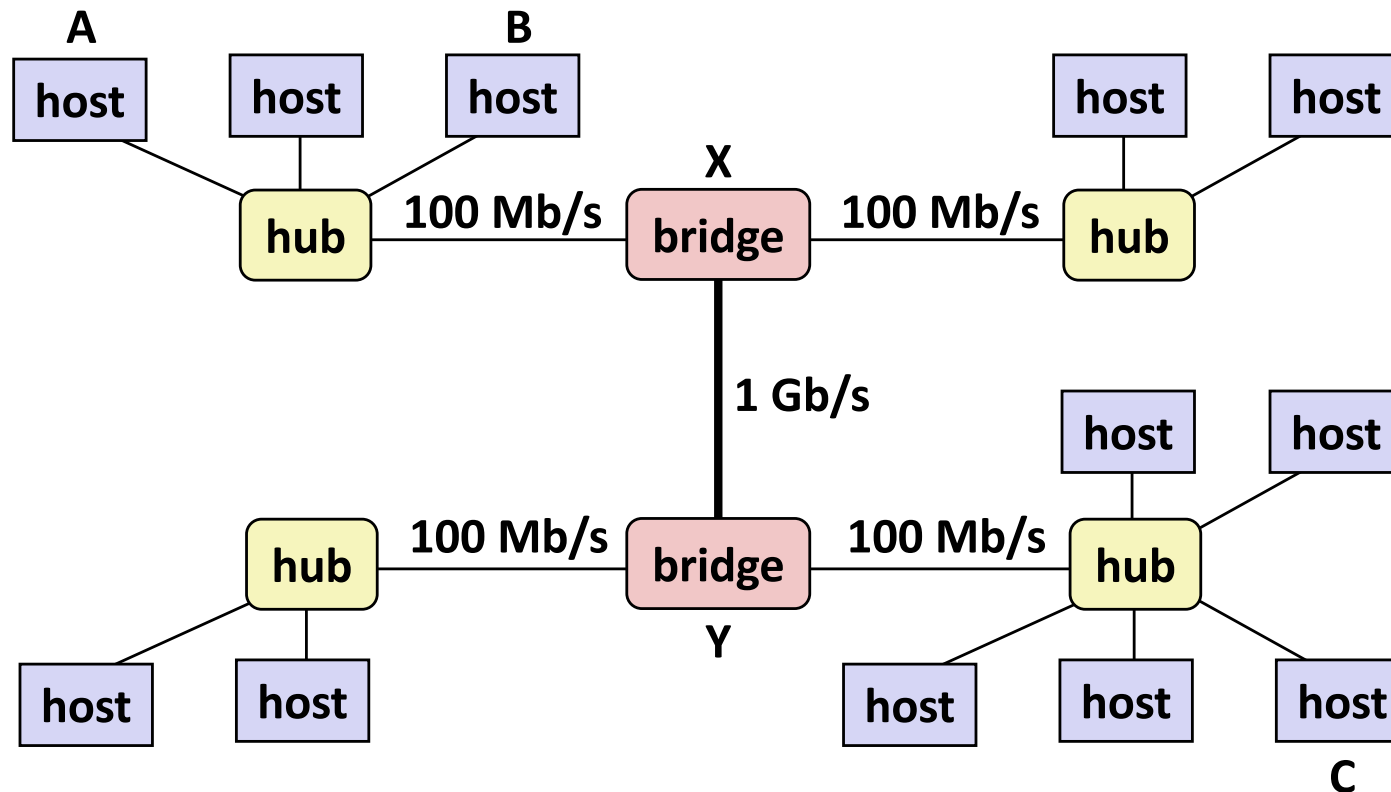
- A ***network*** is a hierarchical system of boxes and wires organized by geographical proximity
 - SAN (System Area Network) spans cluster or machine room
 - Switched Ethernet, Quadrics QSW, ...
 - LAN (Local Area Network) spans a building or campus
 - Ethernet is most prominent example
 - WAN (Wide 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 an internet is built 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
- 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*
 - Hub slavishly copies each bit from each port to every other port
 - Every host sees every bit
 - Note: Hubs are on their way out. Bridges (switches, routers) became cheap enough to replace them

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

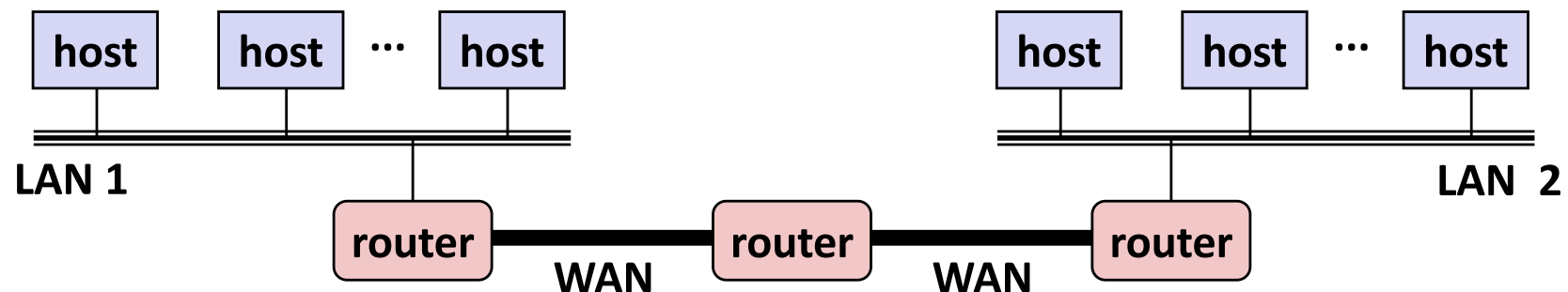
Conceptual View of LANs

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



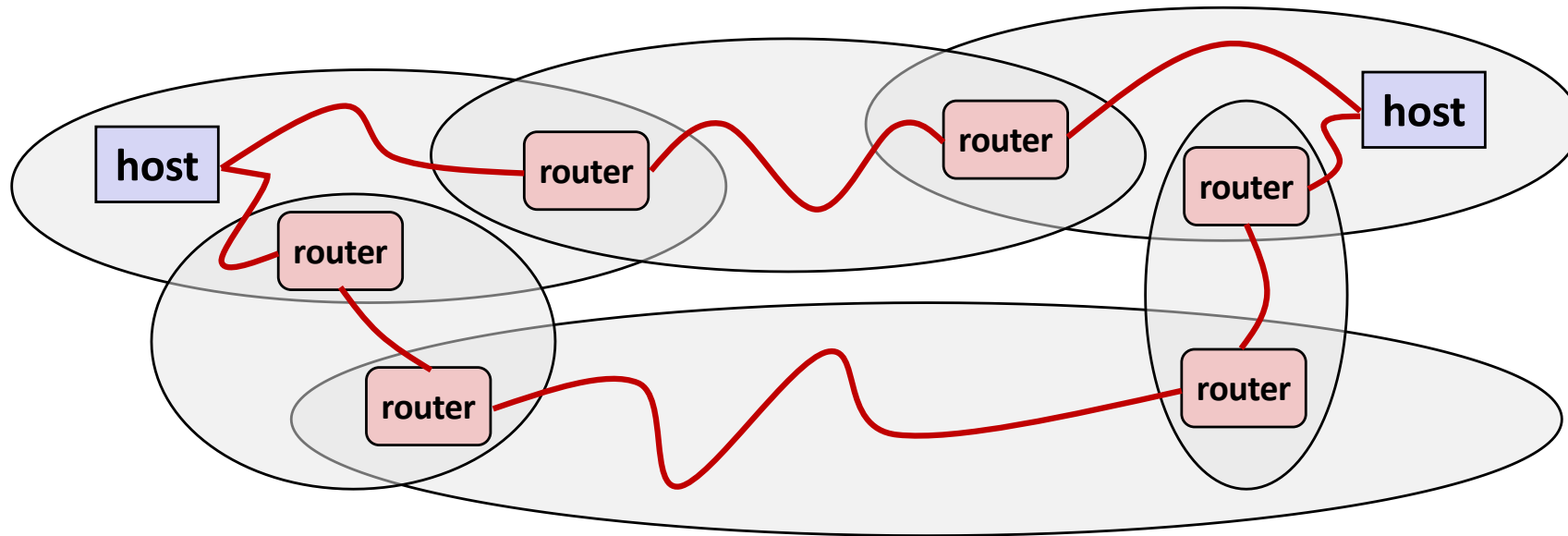
Next Level: internets

- Multiple incompatible LANs can be physically connected by specialized computers called ***routers***
- The connected networks are called an ***internet*** (lower case)



LAN 1 and LAN 2 might be completely different, totally incompatible (e.g., Ethernet, Fibre 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: *protocol* software running on each host and router
 - Protocol is a set of rules that governs how hosts and routers should cooperate when they transfer data from network to network.
 - Smooths out the differences between the different networks

What Does an internet Protocol Do?

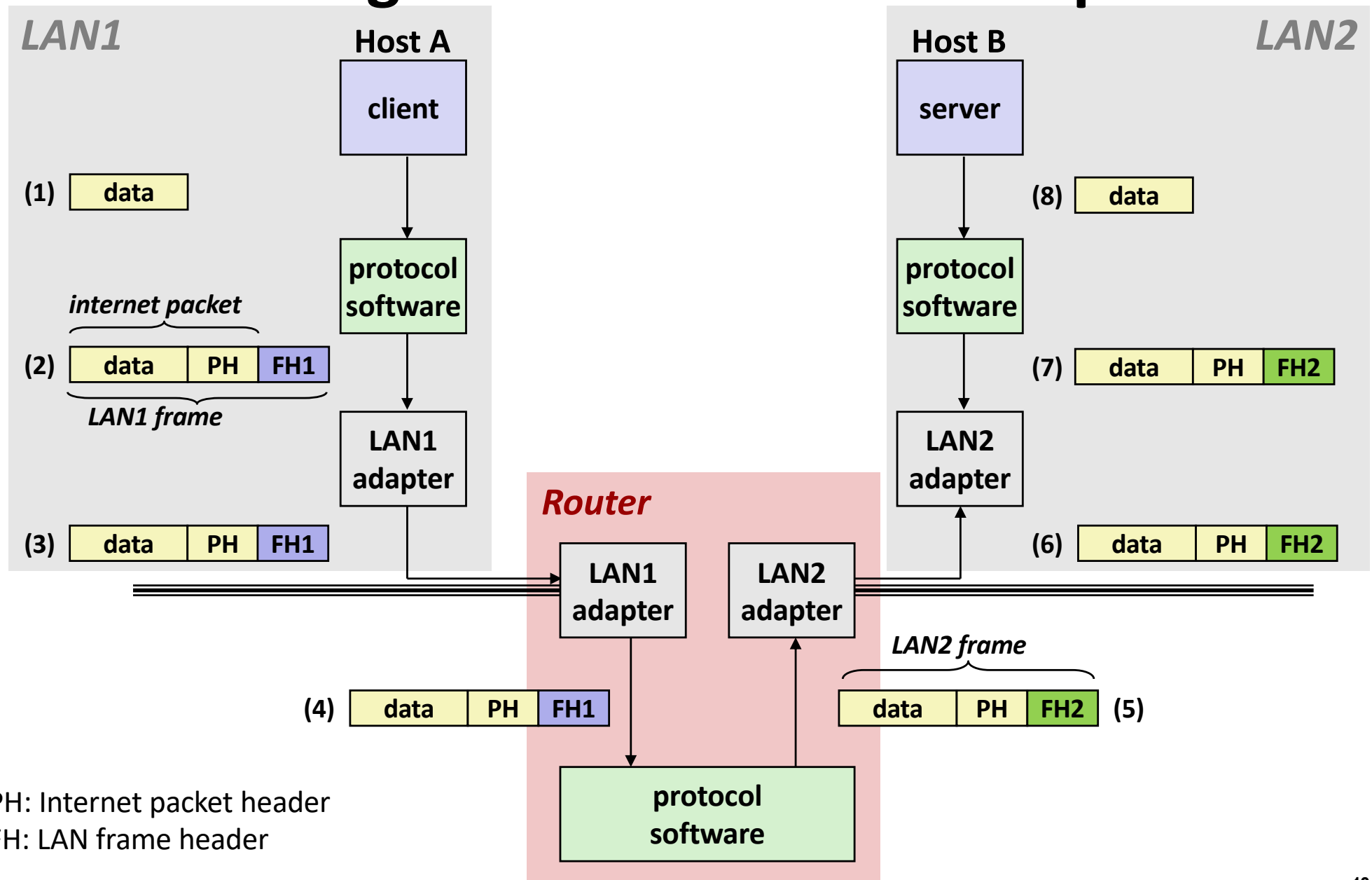
■ Provides a *naming scheme*

- 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

Transferring internet Data Via Encapsulation



Other Issues

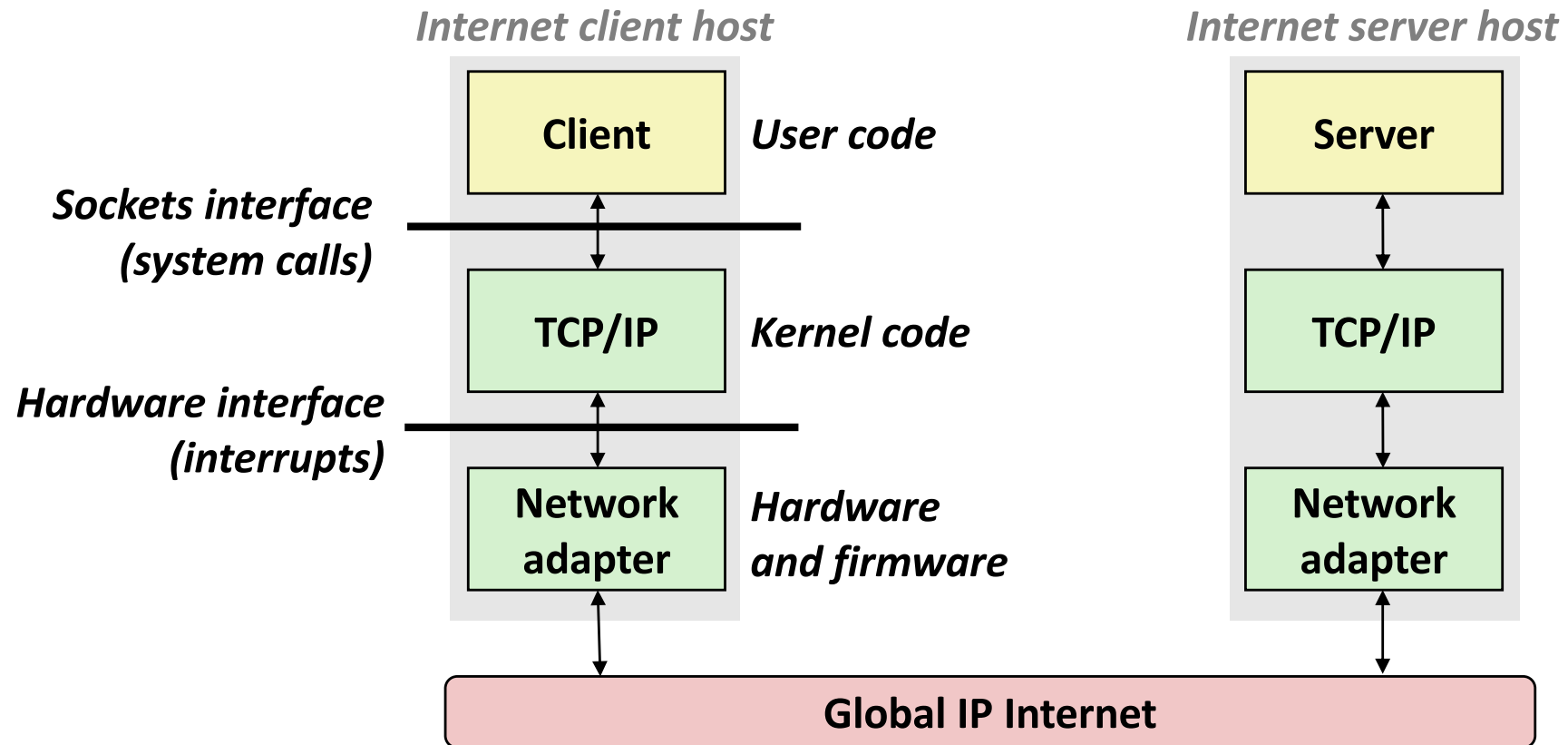
- **We are glossing over a number of important questions:**
 - What if different networks have different maximum frame sizes? (segmentation)
 - How do routers know where to forward frames?
 - How are routers informed when the network topology changes?
 - What if packets get lost?

- **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. 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*

Aside: 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
- As of 2015, vast majority of Internet traffic still carried by IPv4
 - Only 4% of users access Google services using IPv6.
- We will focus on IPv4, but will show you how to write networking code that is protocol-independent.

(1) IP Addresses

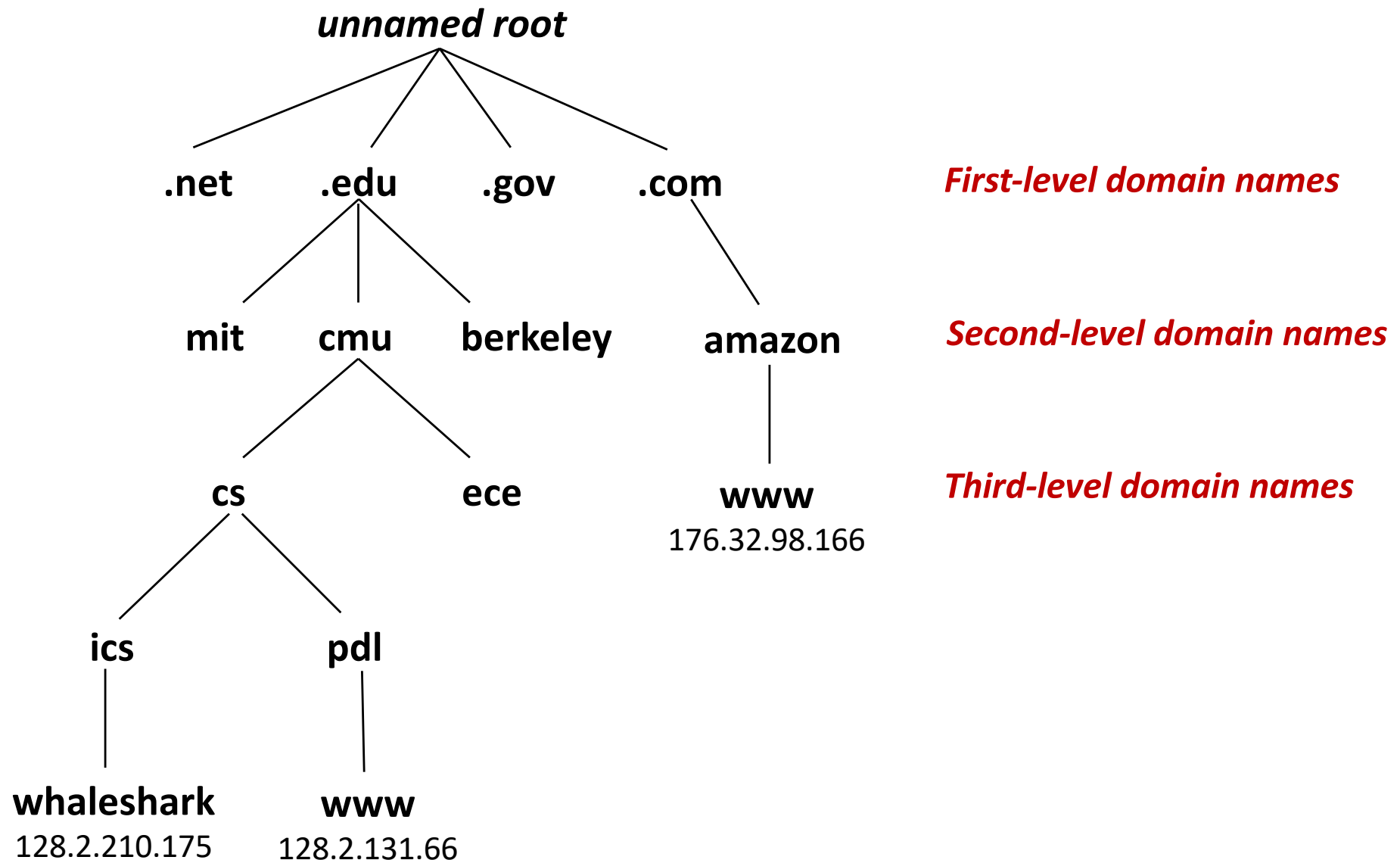
- 32-bit IP addresses are stored in an *IP address struct*
 - IP addresses are always stored in memory in *network byte order* (big-endian byte order)
 - True in general for any integer transferred in a packet header from one machine to another.
 - E.g., the port number used to identify an Internet connection.

```
/* 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



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: 199.16.156.6
Address: 199.16.156.70
Address: 199.16.156.102
Address: 199.16.156.230
```

```
linux> nslookup twitter.com
Address: 199.16.156.102
Address: 199.16.156.230
Address: 199.16.156.6
Address: 199.16.156.70
```

- 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
```


(3) Internet Connections

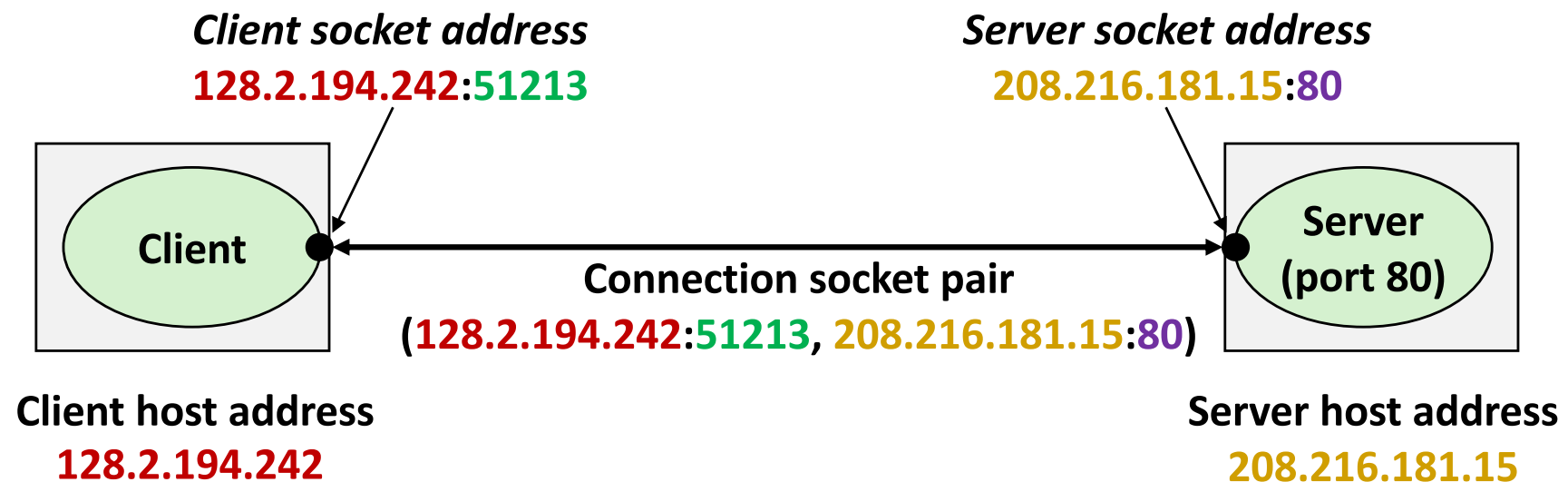
- Clients and servers communicate by sending streams of bytes over **connections**. Each connection is:
 - *Point-to-point*: connects a pair of processes.
 - *Full-duplex*: data can flow in both directions at the same time,
 - *Reliable*: stream of bytes sent by the source is eventually received by the 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
- Mappings between well-known ports and service names is contained in the file `/etc/services` on each Linux machine.

Anatomy of a Connection

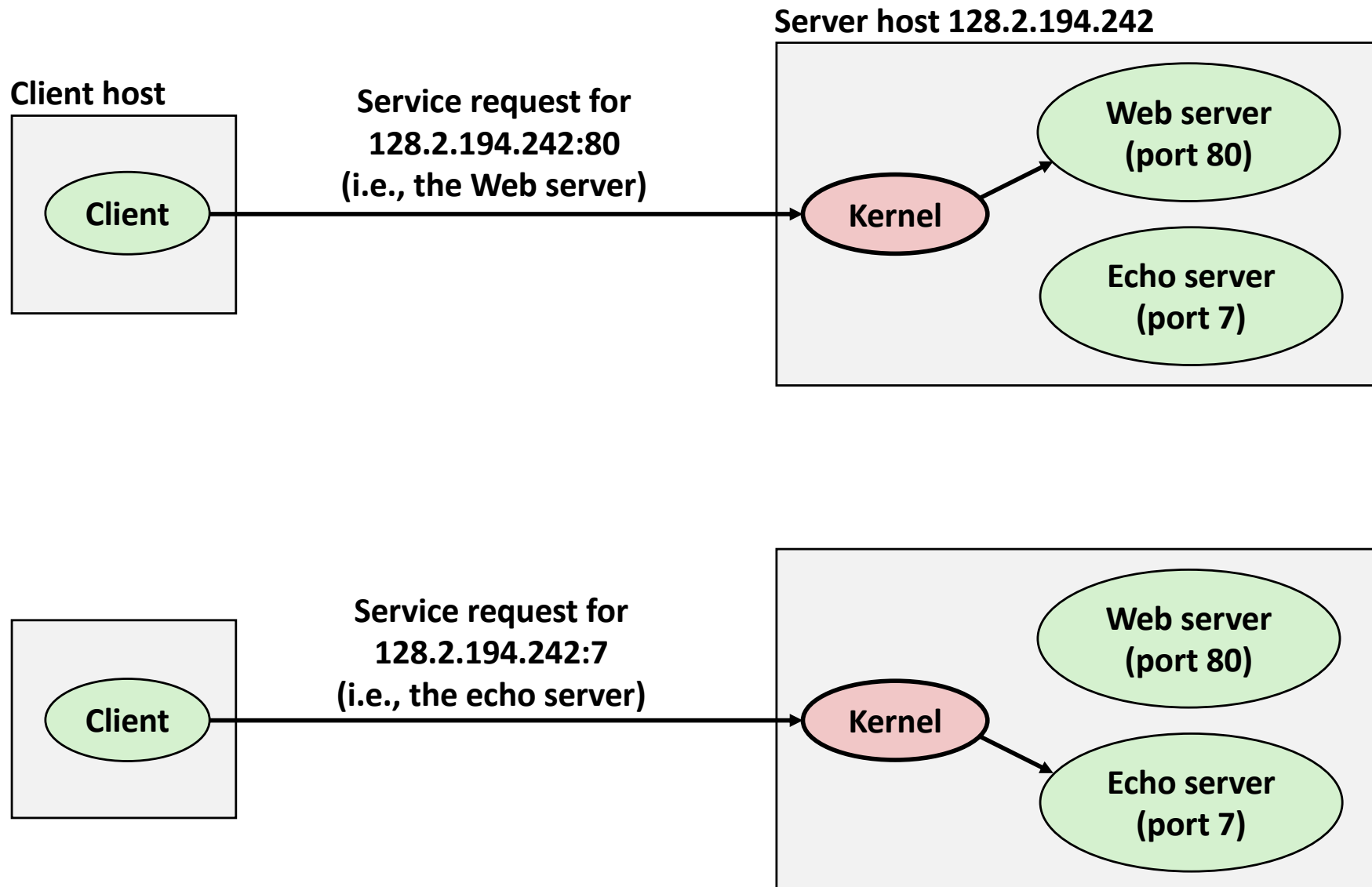
- A connection is uniquely identified by the socket addresses of its endpoints (*socket pair*)
 - (cliaddr:cliport, servaddr:servport)



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

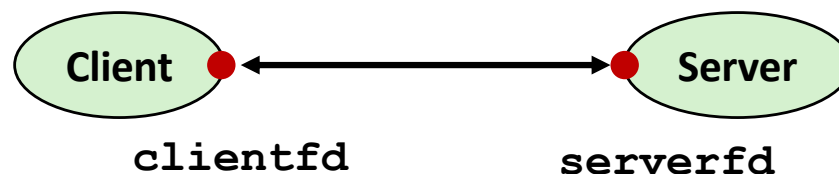
- Set of system-level functions used in conjunction with Unix I/O to build network applications.
- Created in the early 80's as part of the original Berkeley distribution of Unix that contained an early version of the Internet protocols.
- Available on all modern systems
 - Unix variants, Windows, OS X, IOS, Android, ARM

Sockets

■ 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 Address Structures

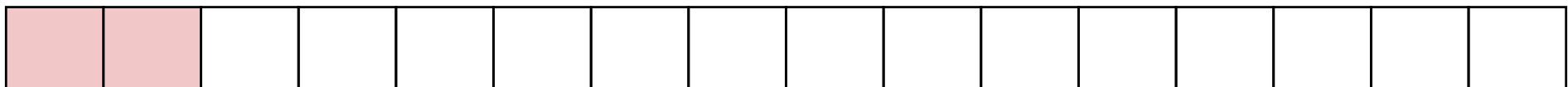
■ Generic socket address:

- 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



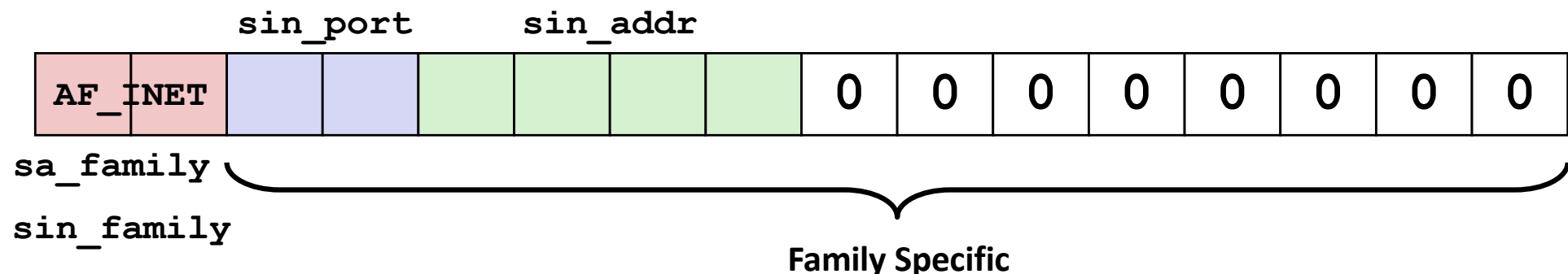
Family Specific

Socket Address Structures

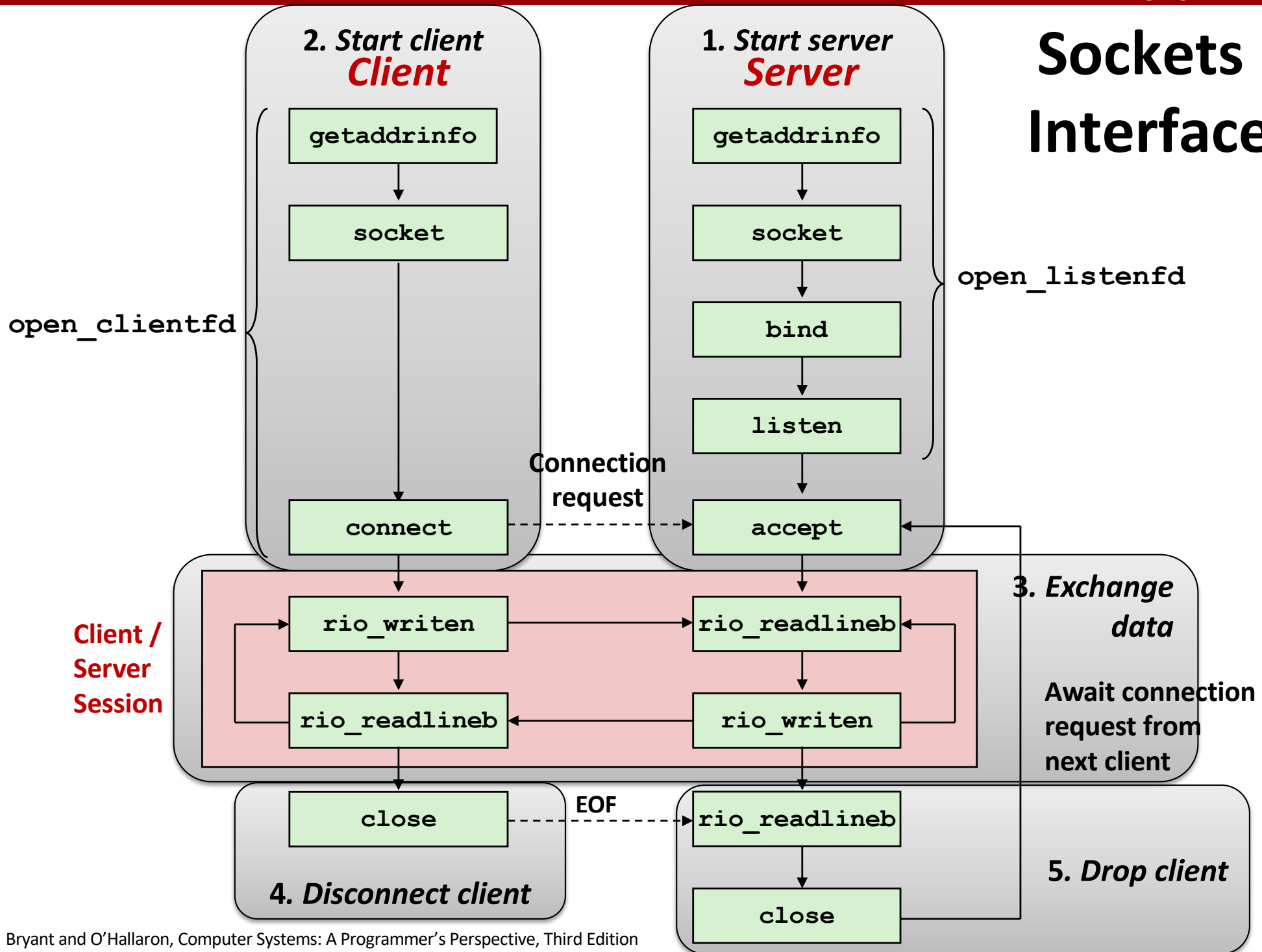
■ Internet-specific socket address:

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

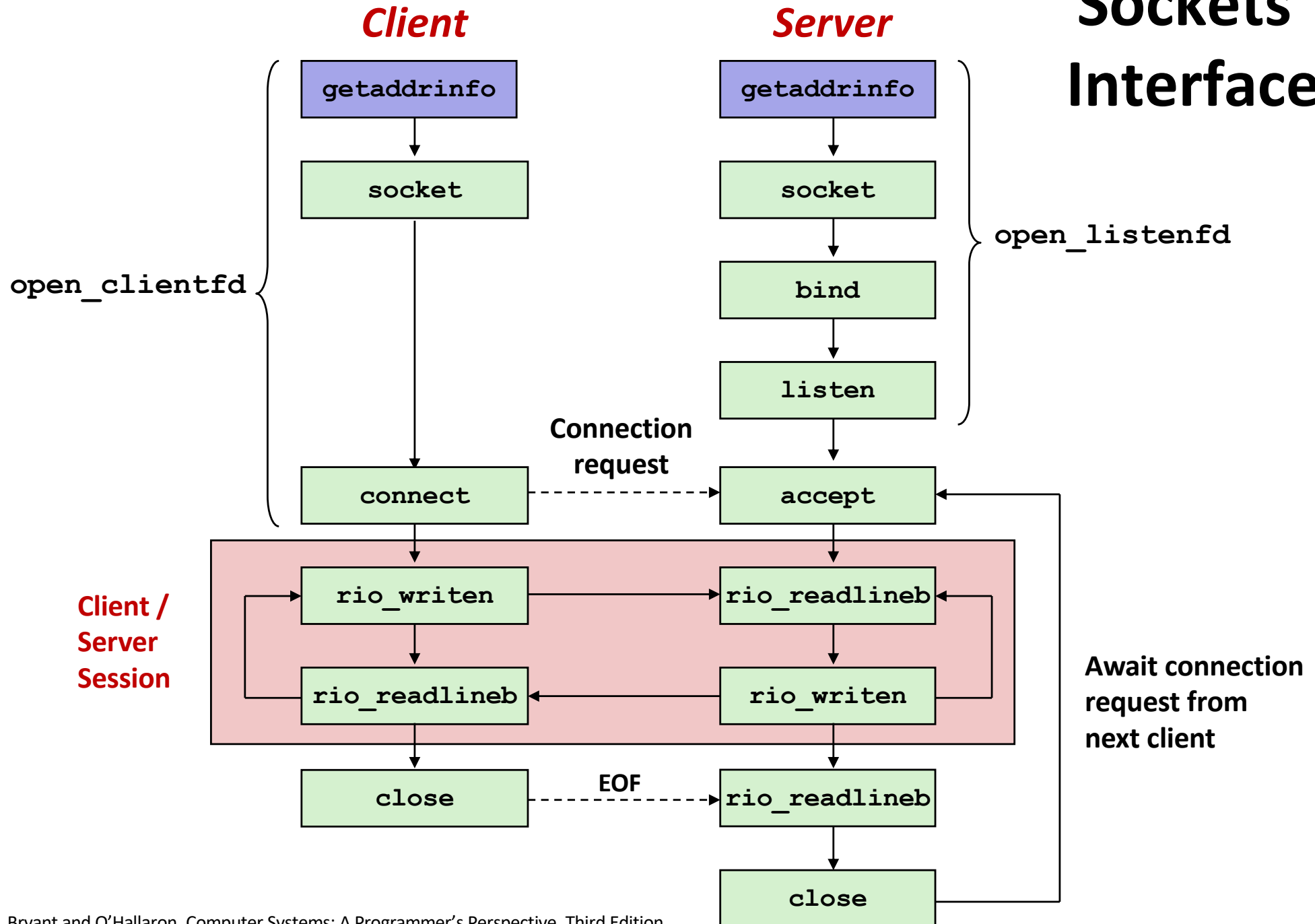
```
struct sockaddr_in {
    uint16_t      sin_family; /* Protocol family (always AF_INET) */
    uint16_t      sin_port;   /* Port num in network byte order */
    struct in_addr sin_addr;   /* IP addr in network byte order */
    unsigned char sin_zero[8]; /* Pad to sizeof(struct sockaddr) */
};
```



Sockets Interface



Sockets Interface



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

Host and Service Conversion: getaddrinfo

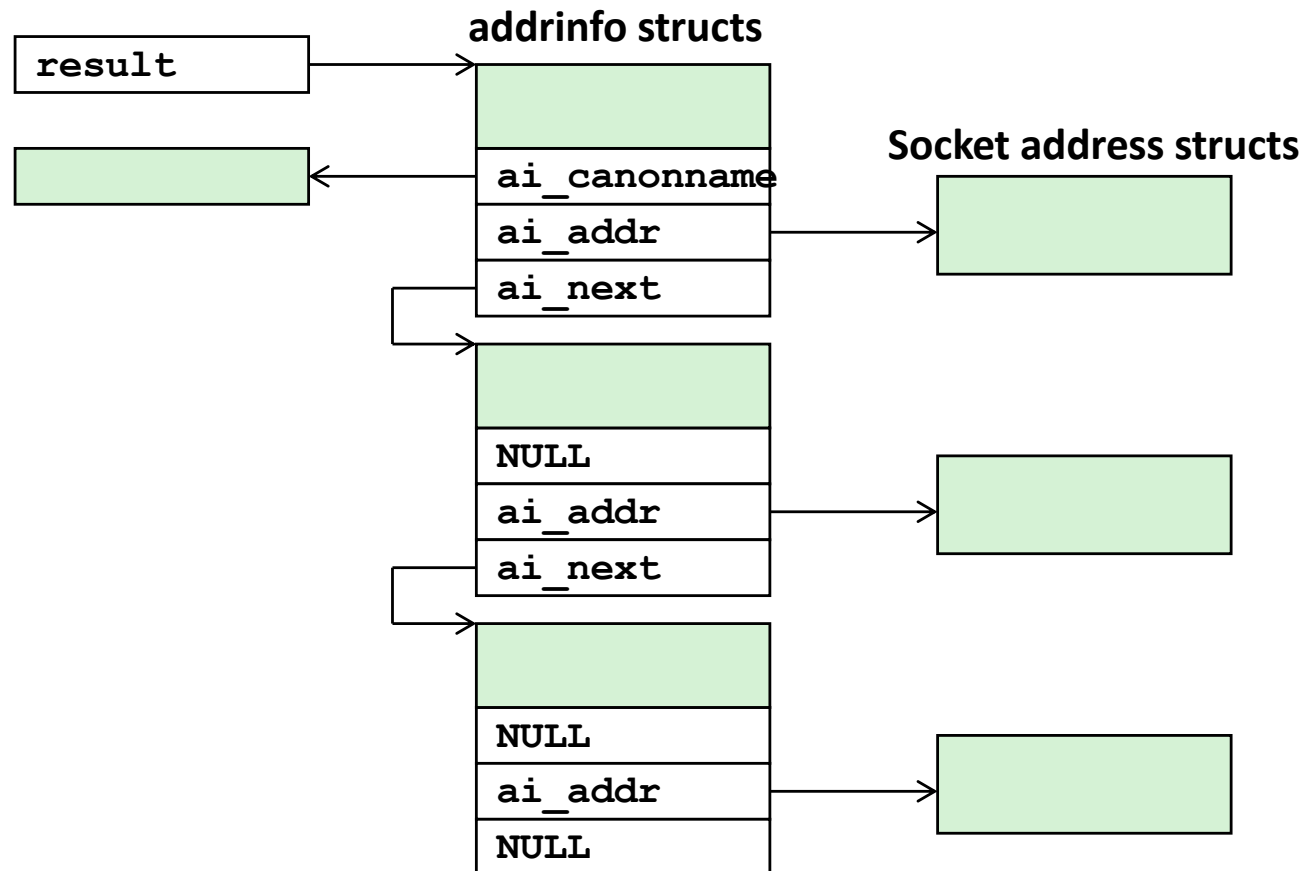
```
int getaddrinfo(const char *host,          /* Hostname or address */
               const char *service,       /* Port or service name
*/
               const struct addrinfo *hints, /* Input parameters */
               struct addrinfo **result);   /* Output linked list */

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!