

# Network Programming: Part I

15-213: Introduction to Computer Systems  
21<sup>st</sup> Lecture, March 31, 2016

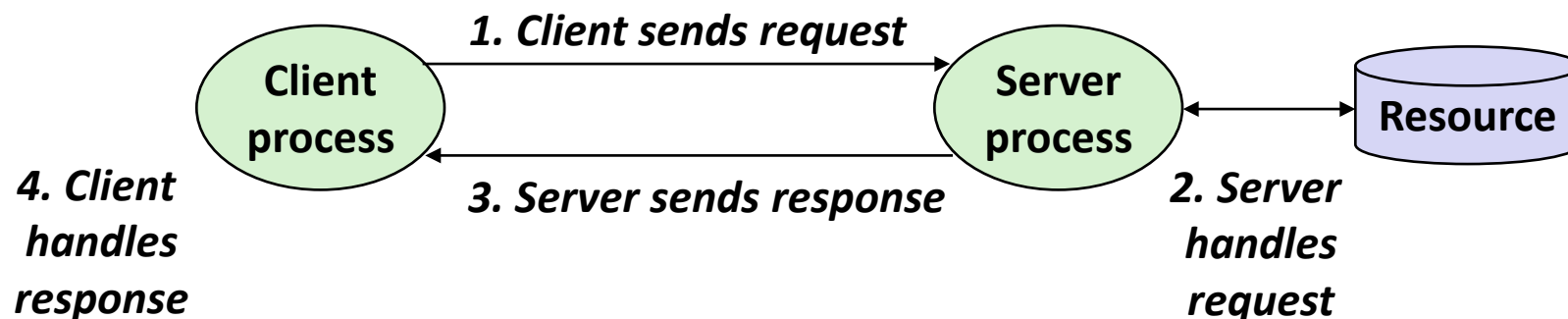
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# A Client-Server Transaction

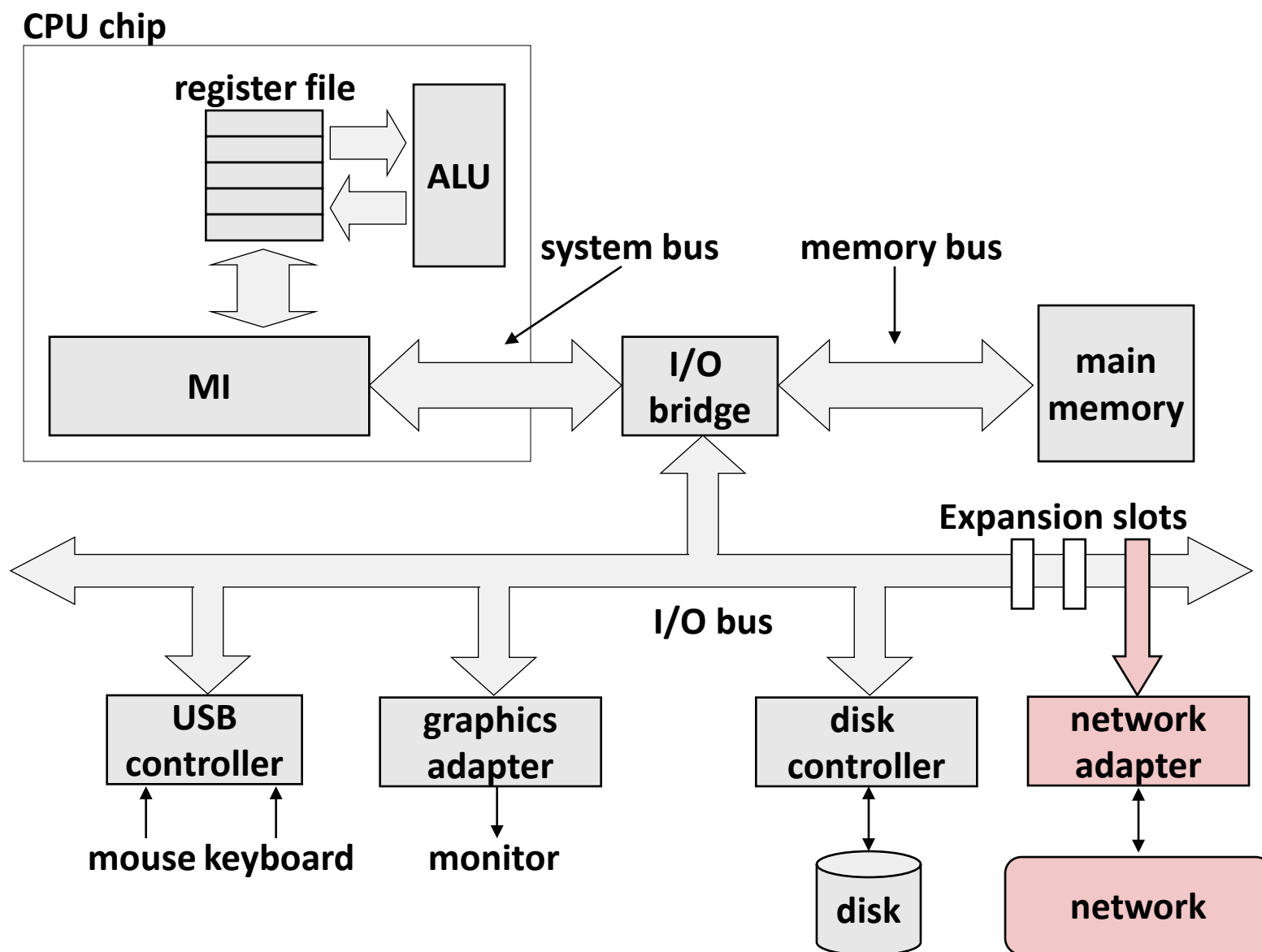
## ■ Most network applications are based on the client-server model:

- 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)

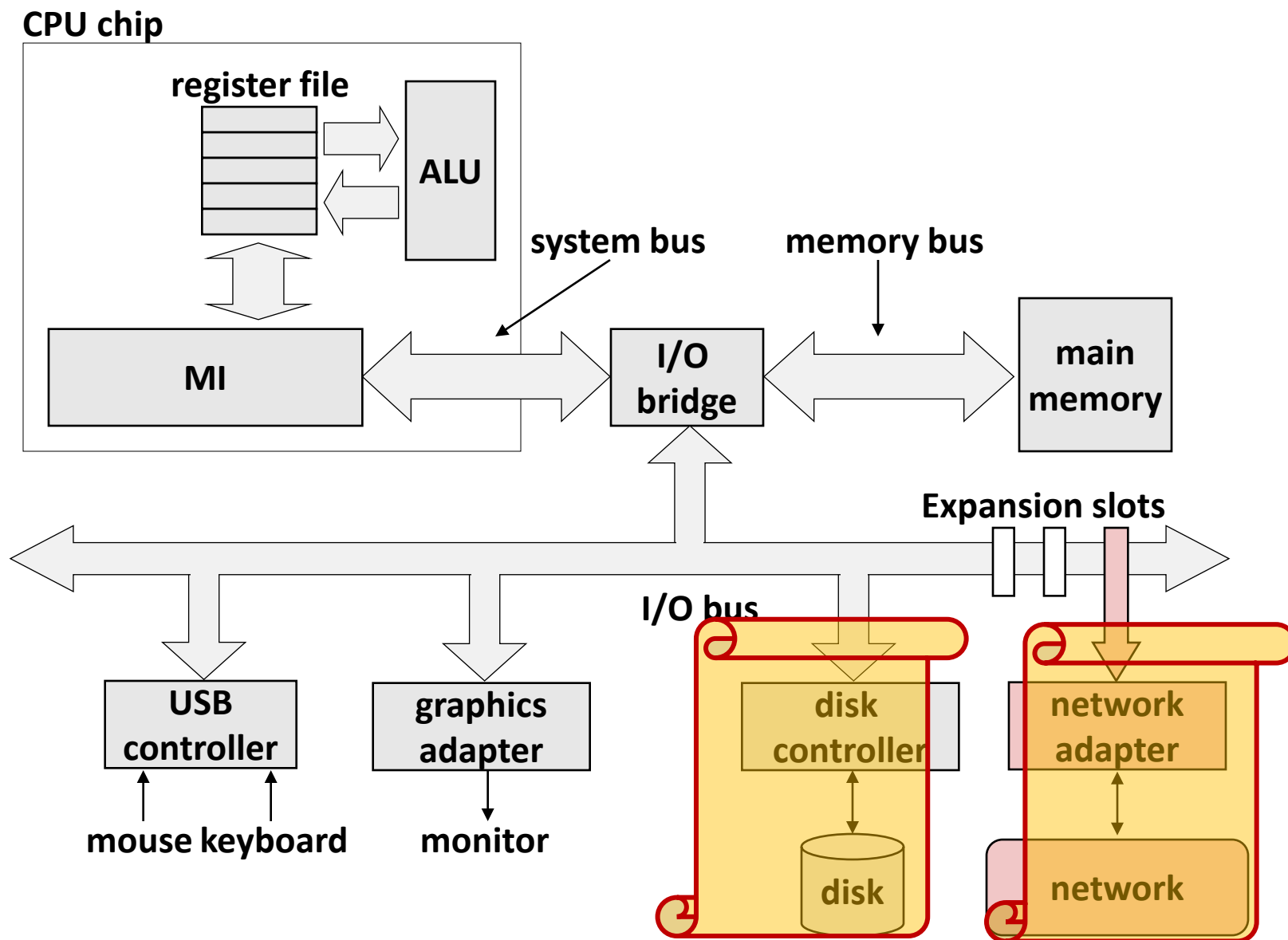


*Note: clients and servers are processes running on hosts  
(can be the same or different hosts)*

# Hardware Organization of a Network Host



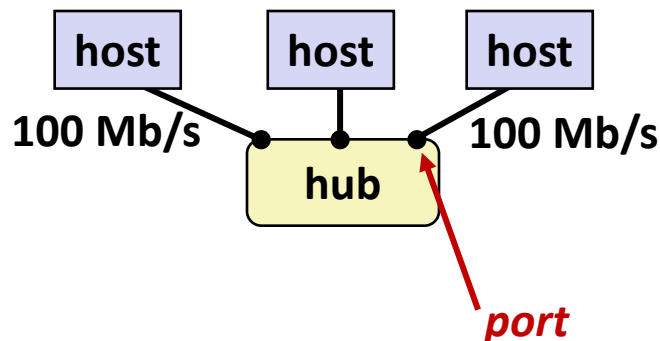
# Hardware Organization of a Network Host



# Computer Networks

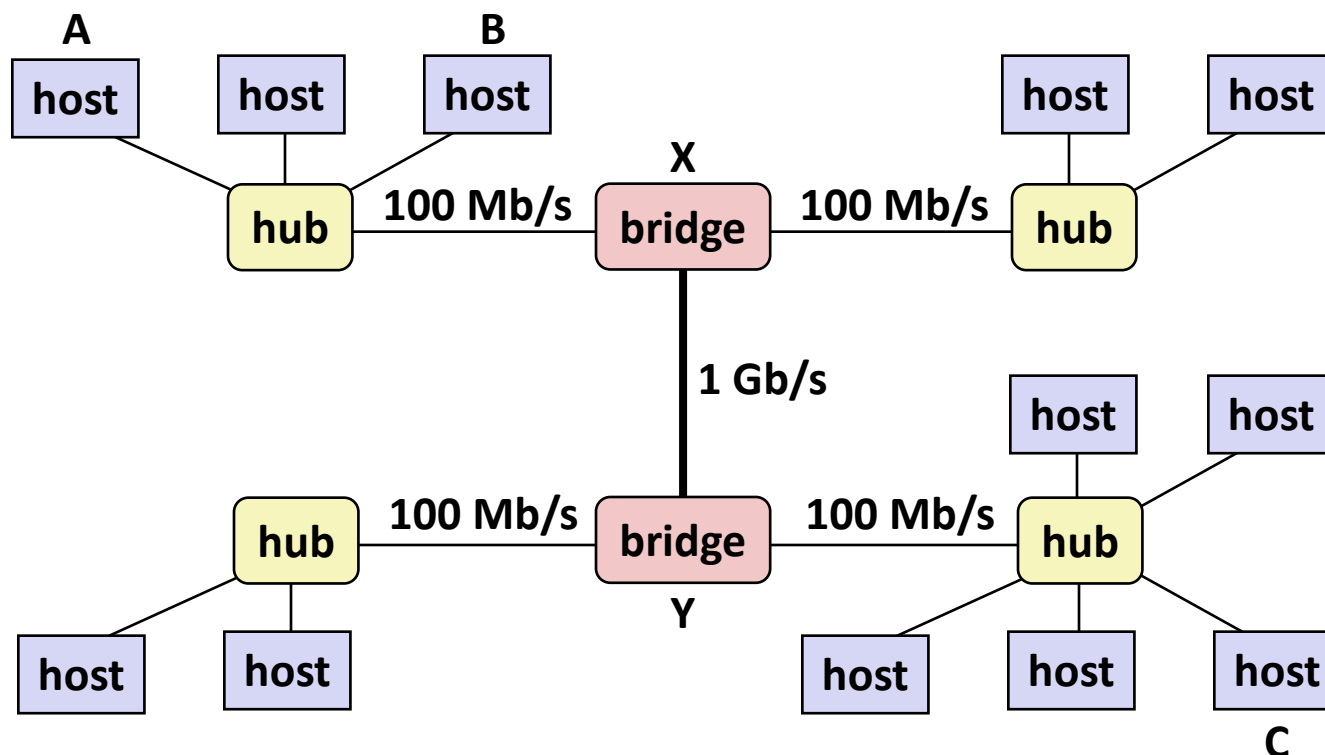
- A ***network*** is a hierarchical system of boxes and wires organized by geographical proximity
  - SAN (System Area Network) spans cluster or machine room
    - Switched Ethernet, Quadrics QSW, ...
  - LAN (Local Area Network) spans a building or campus
    - Ethernet is most prominent example
  - 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

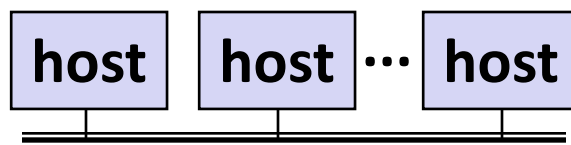
# Next Level: Bridged Ethernet Segment



- 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

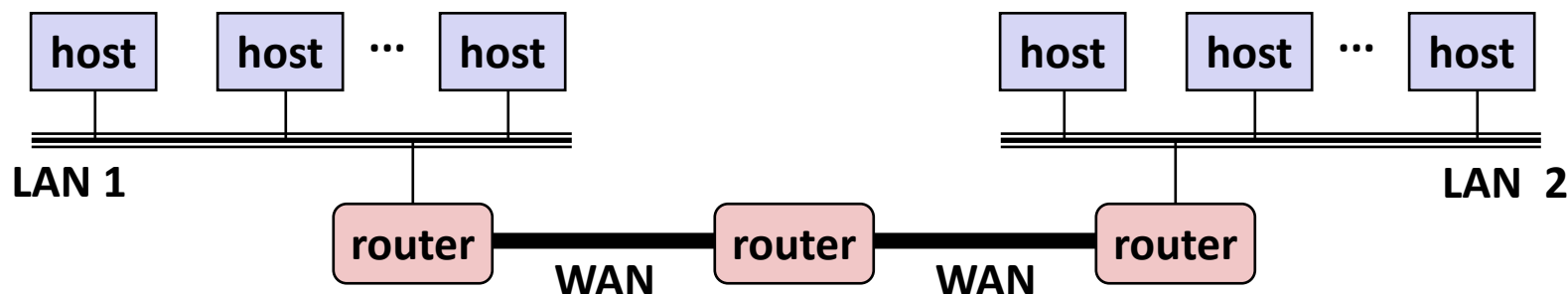
- For simplicity, hubs, bridges, and wires are often shown as a collection of hosts attached to a single wire:





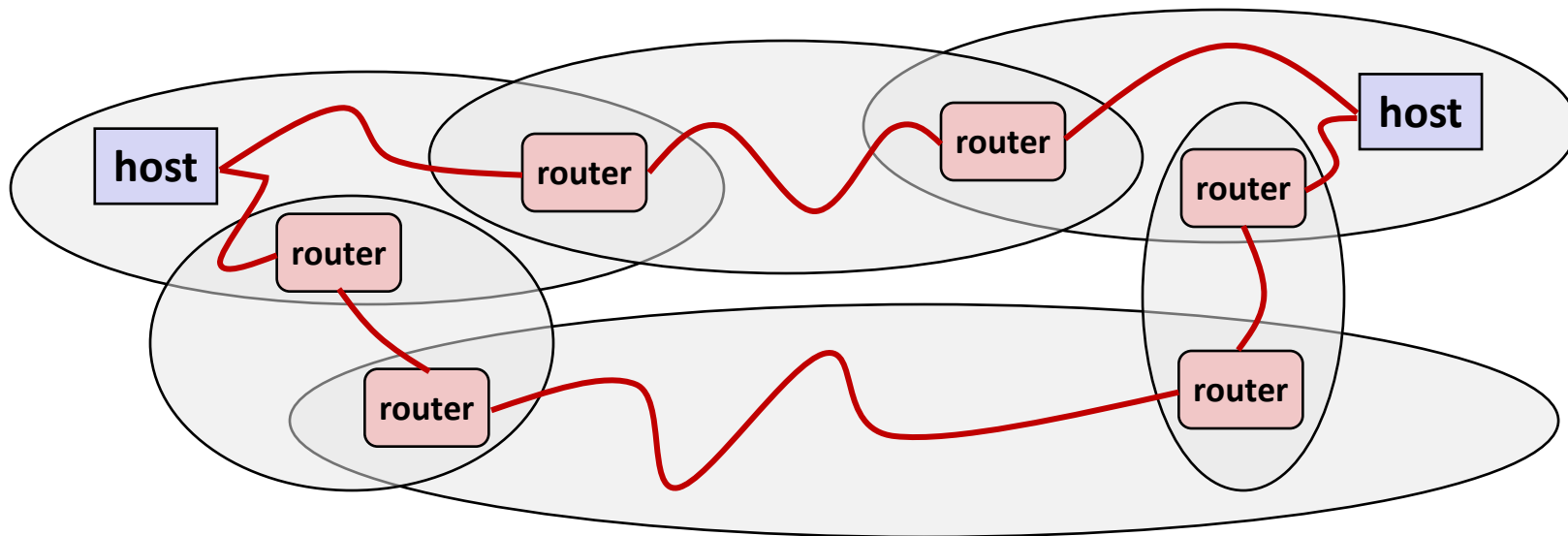
# Next Level: internets

- 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

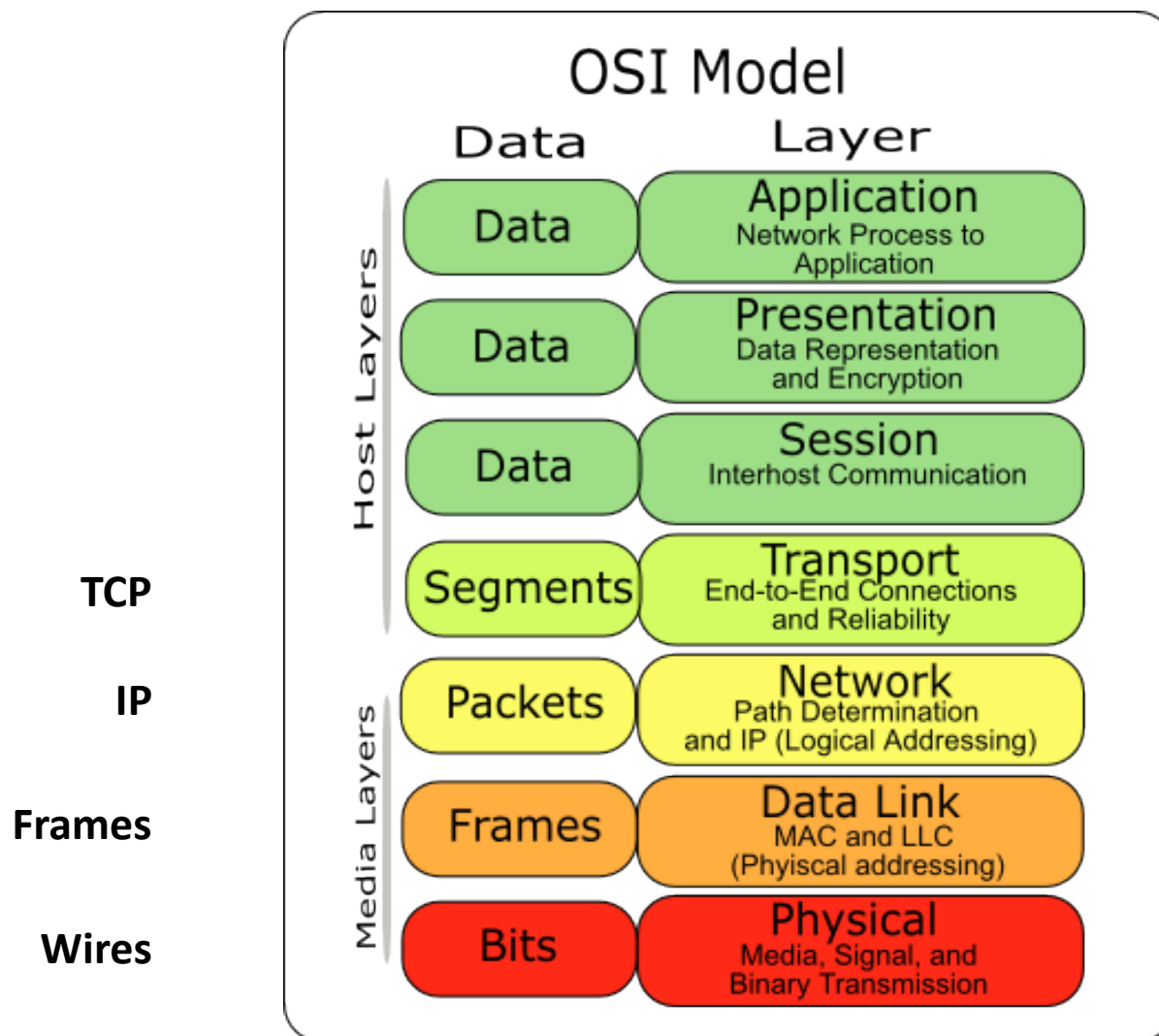
## ■ Send packets from source to destination by hopping through networks

- 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

# OSI Model



# What Does an internet Protocol Do?

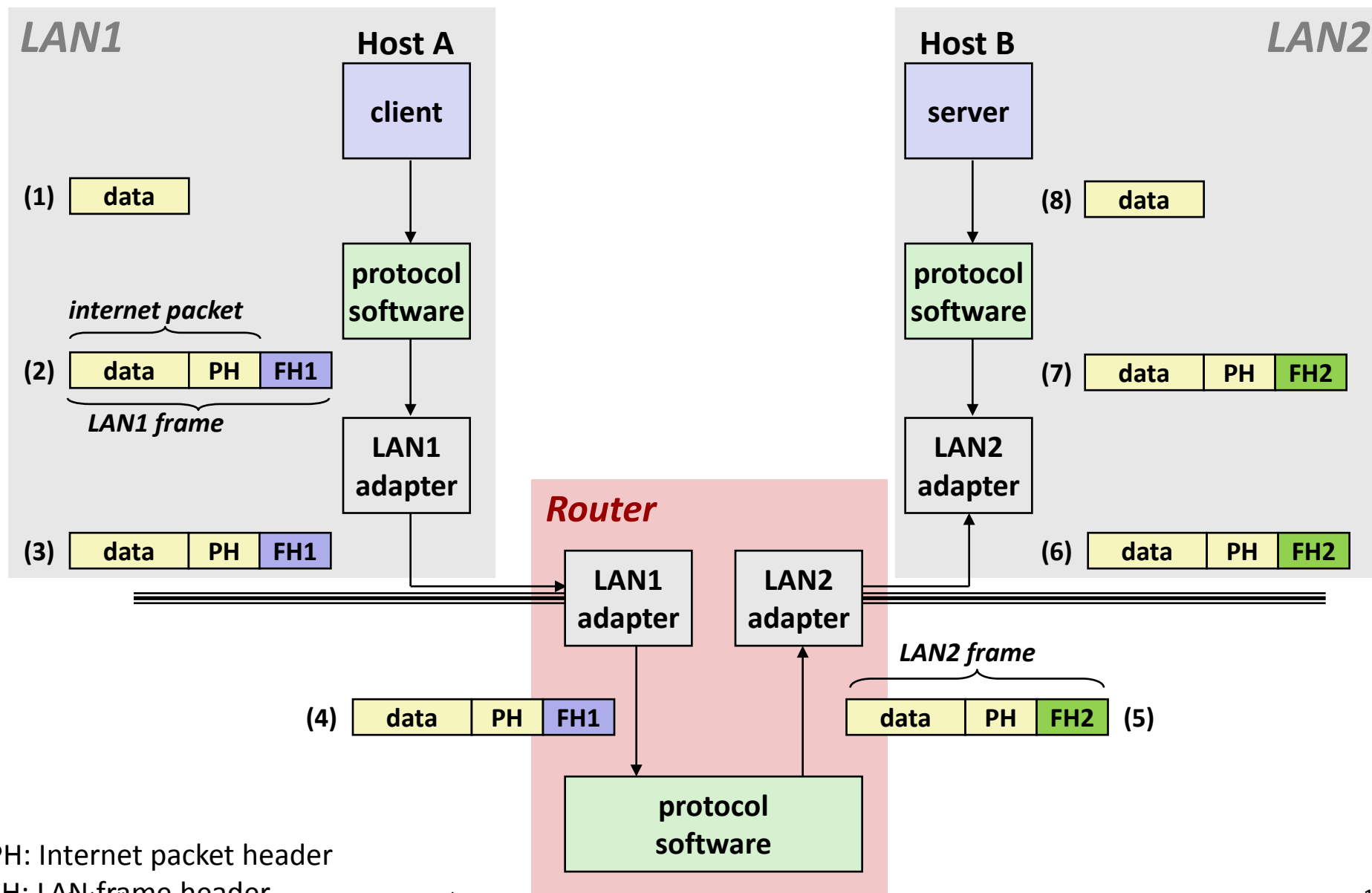
## ■ Provides a *naming scheme*

- 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

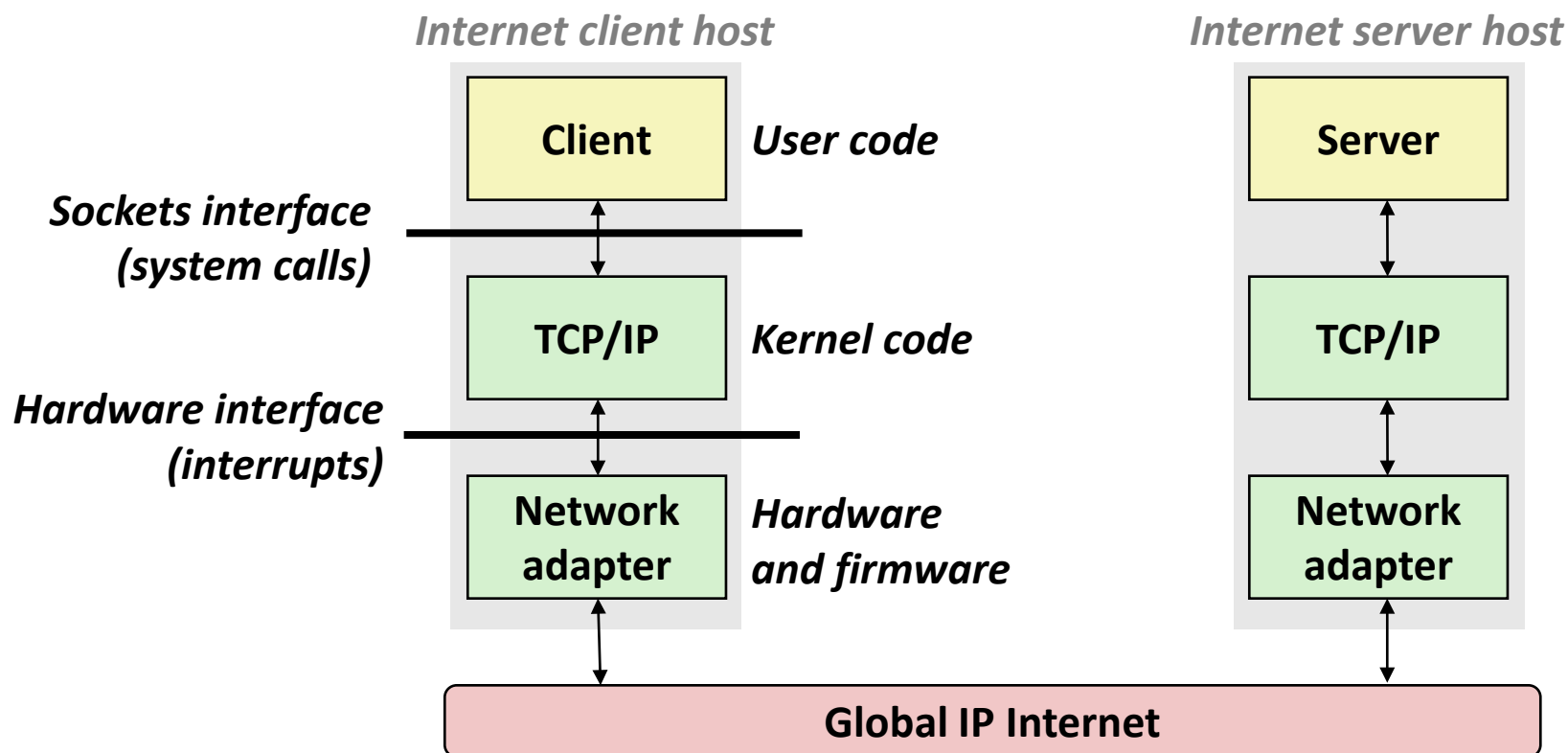
- **We are glossing over a number of important questions:**
  - What if different networks have different maximum frame sizes? (segmentation)
  - How do routers know where to forward frames?
  - How are routers informed when the network topology changes?
  - What if packets get lost?
  
- **These (and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

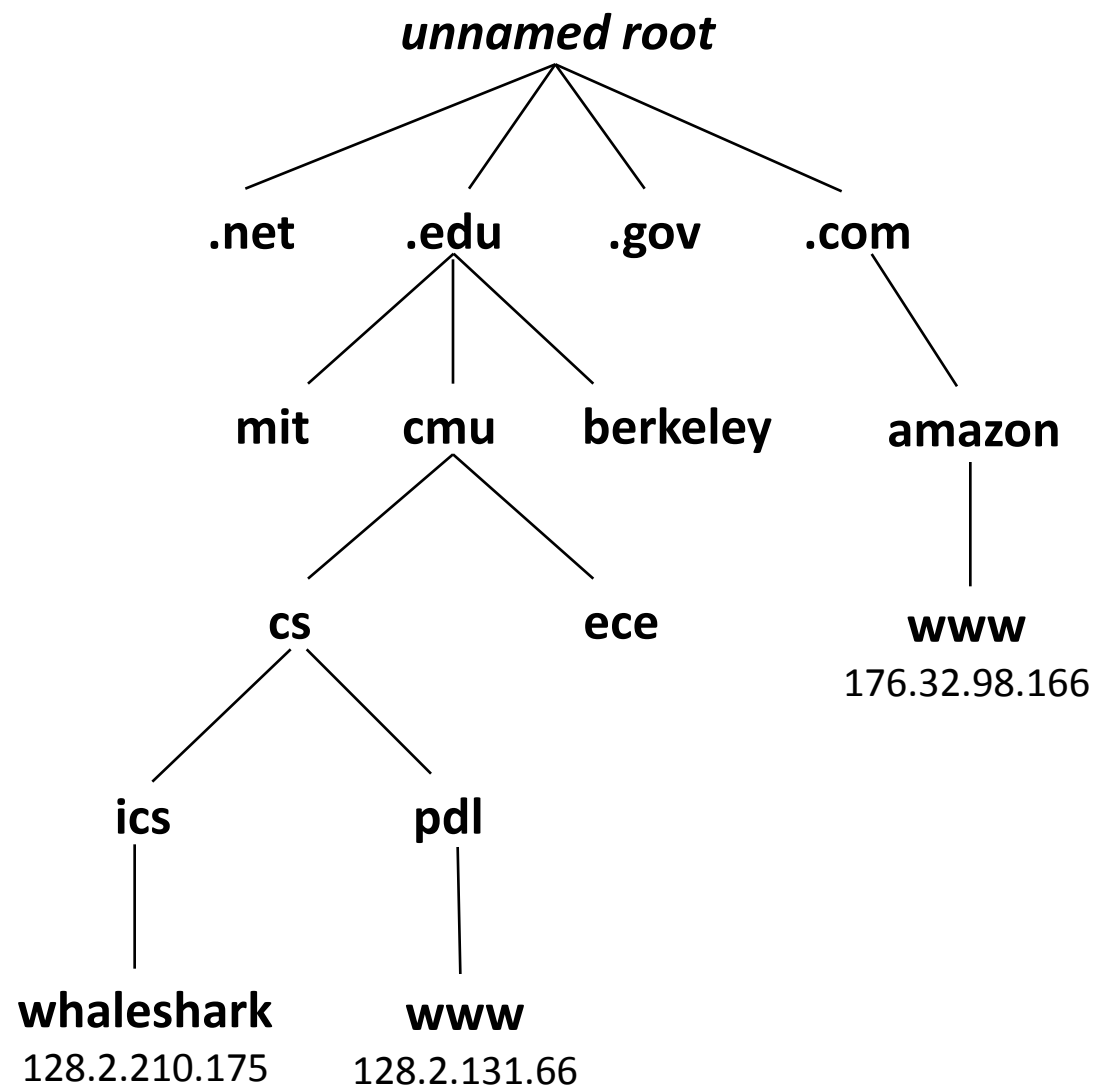
- **32-bit IP addresses are stored in an *IP address struct***
  - IP addresses are always stored in memory in *network byte order* (big-endian byte order)
  - True in general for any integer transferred in a packet header from one machine to another.
    - E.g., the port number used to identify an Internet 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`
- Use `hostname` to determine real domain name of local host:

```
linux> nslookup localhost  
Address: 127.0.0.1
```

```
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

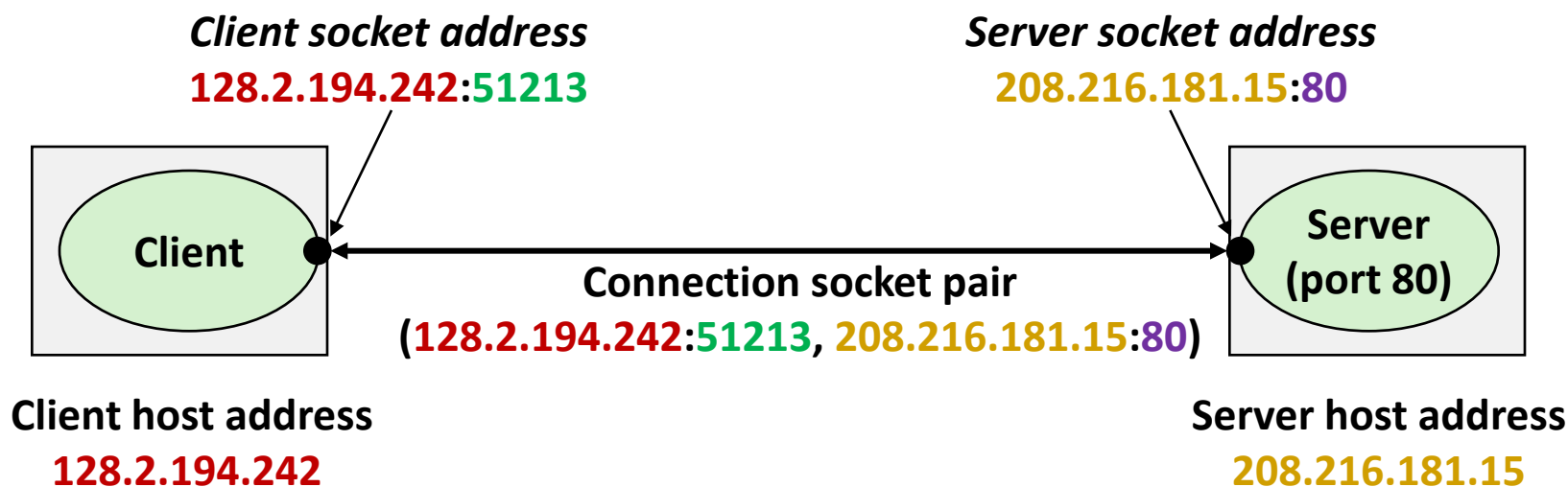
- Clients and servers communicate by sending streams of bytes over **connections**. Each connection is:
  - *Point-to-point*: connects a pair of processes.
  - *Full-duplex*: data can flow in both directions at the same time,
  - *Reliable*: stream of bytes sent by the source is eventually received by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

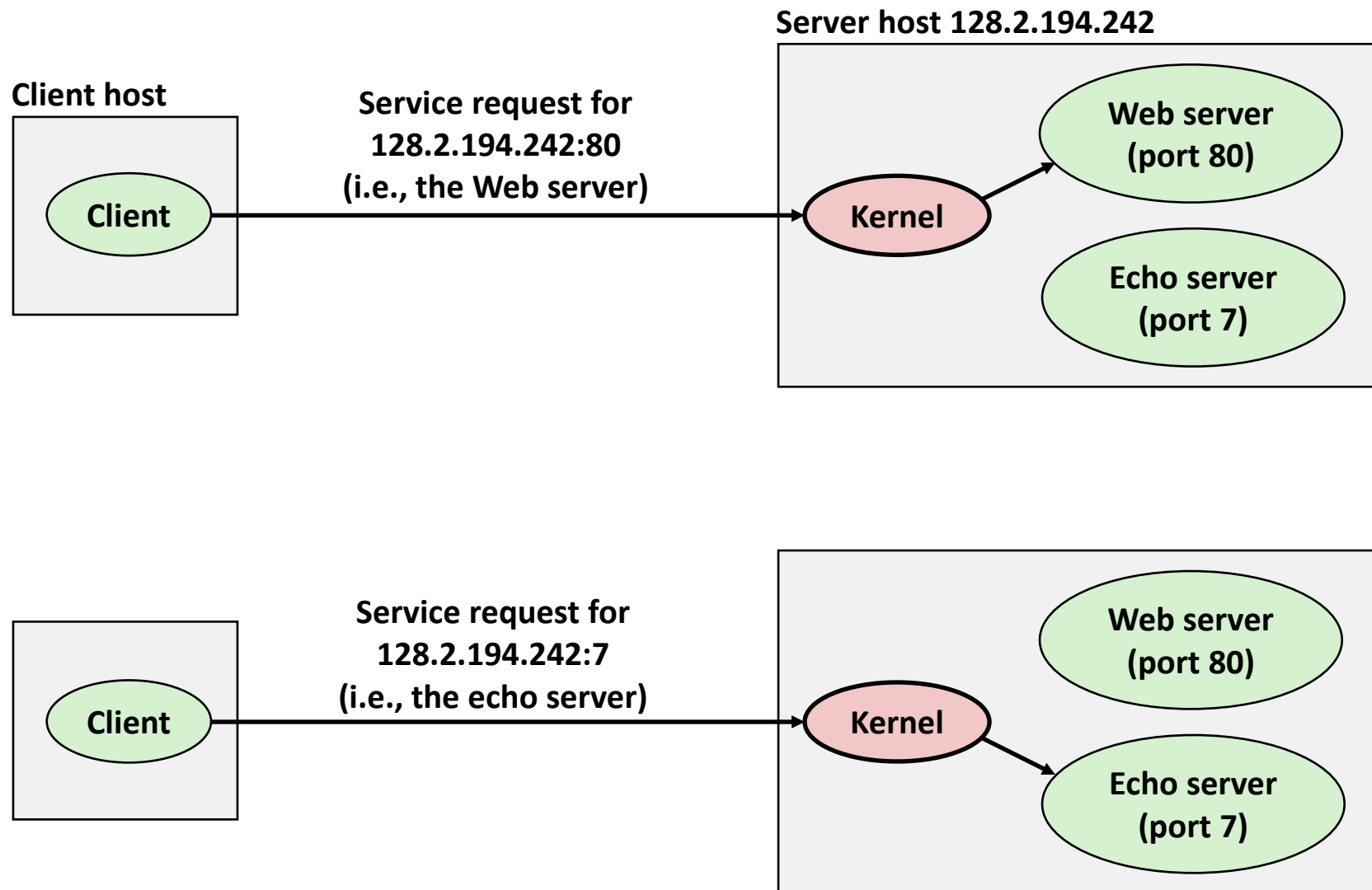
- A connection is uniquely identified by the socket addresses of its endpoints (*socket pair*)
  - (cliaddr:cliport, servaddr:servport)



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**



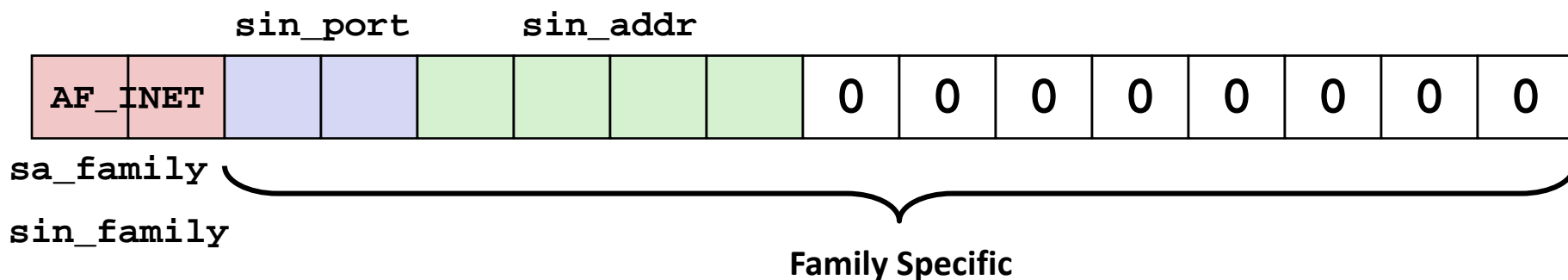
**Family Specific**

# Socket Address Structures

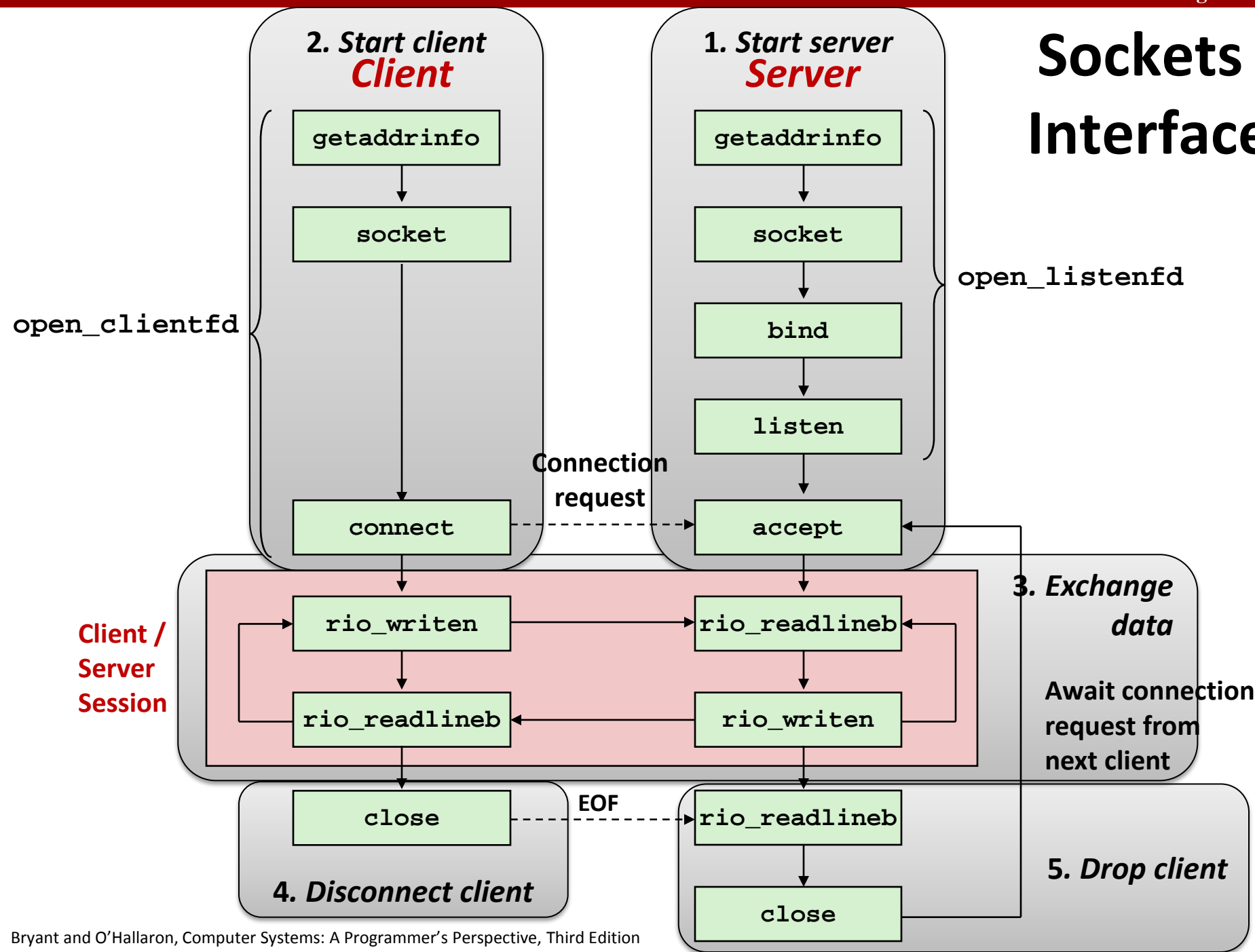
## ■ Internet-specific socket address:

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

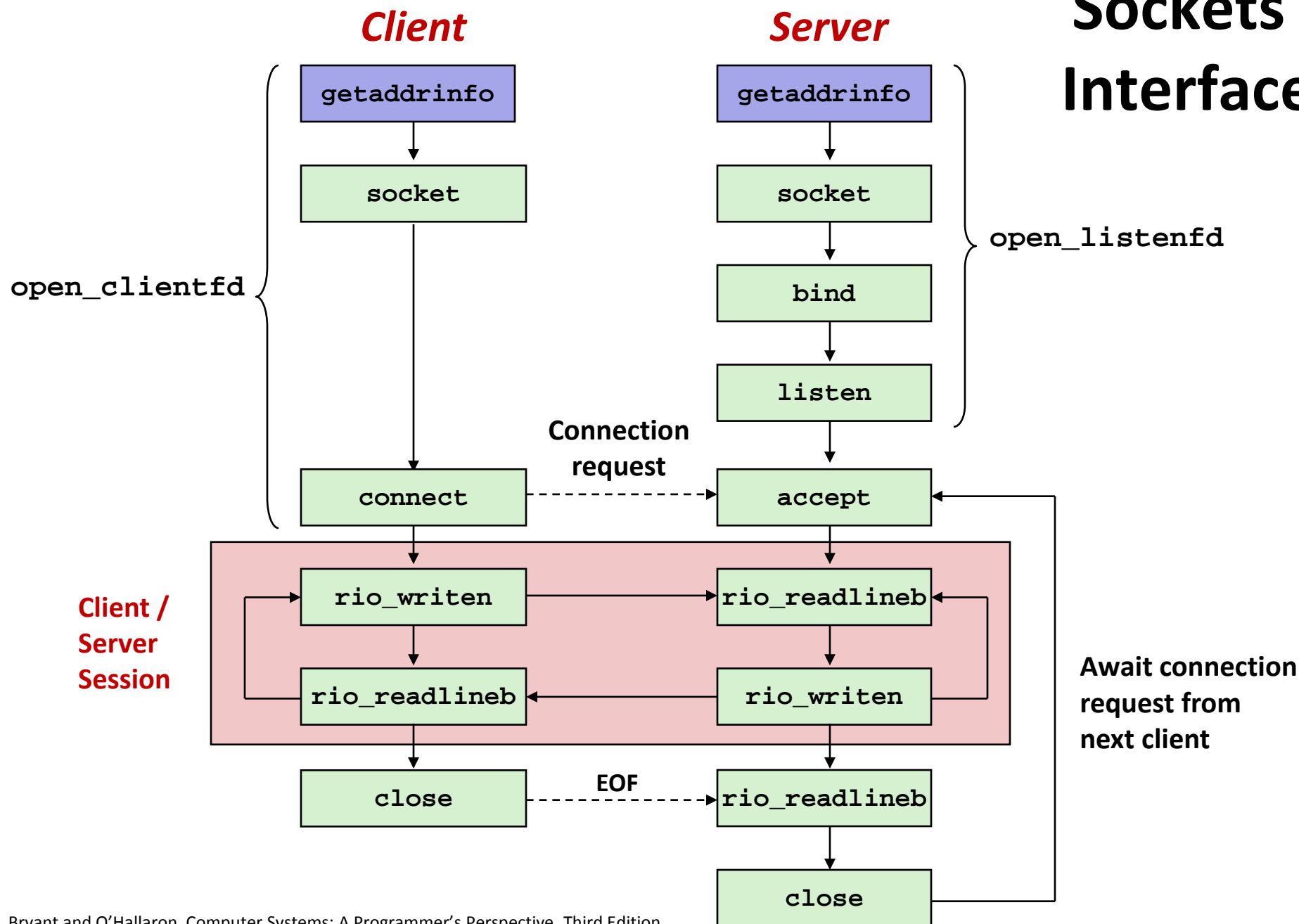
```
struct sockaddr_in {
    uint16_t      sin_family; /* Protocol family (always AF_INET) */
    uint16_t      sin_port;   /* Port num in network byte order */
    struct in_addr sin_addr;   /* IP addr in network byte order */
    unsigned char sin_zero[8]; /* Pad to sizeof(struct sockaddr) */
};
```



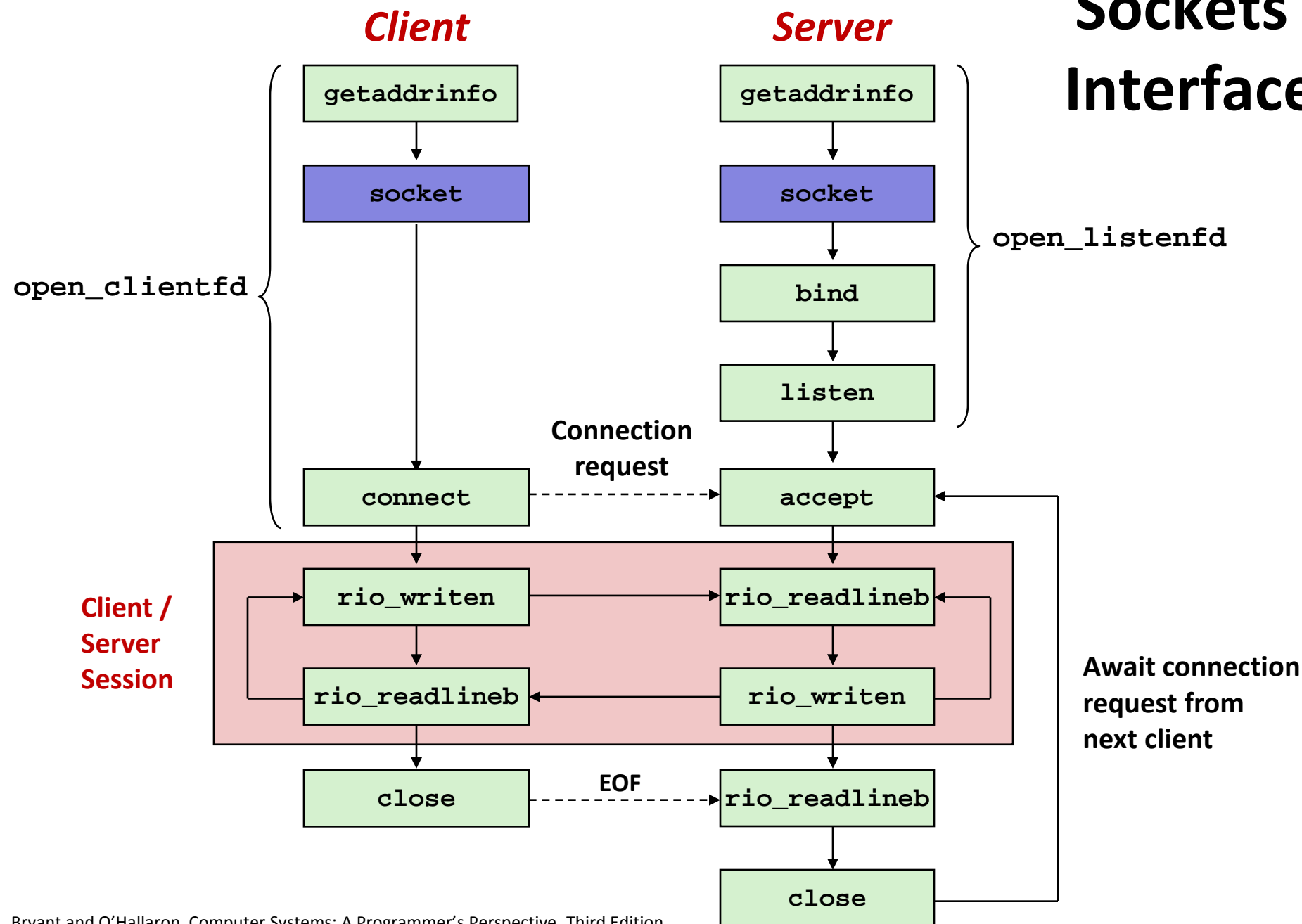
# Sockets Interface



# Sockets Interface



# Sockets Interface



# Sockets Interface: `socket`

- Clients and servers use the `socket` function to create a *socket descriptor*:

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

- Example:

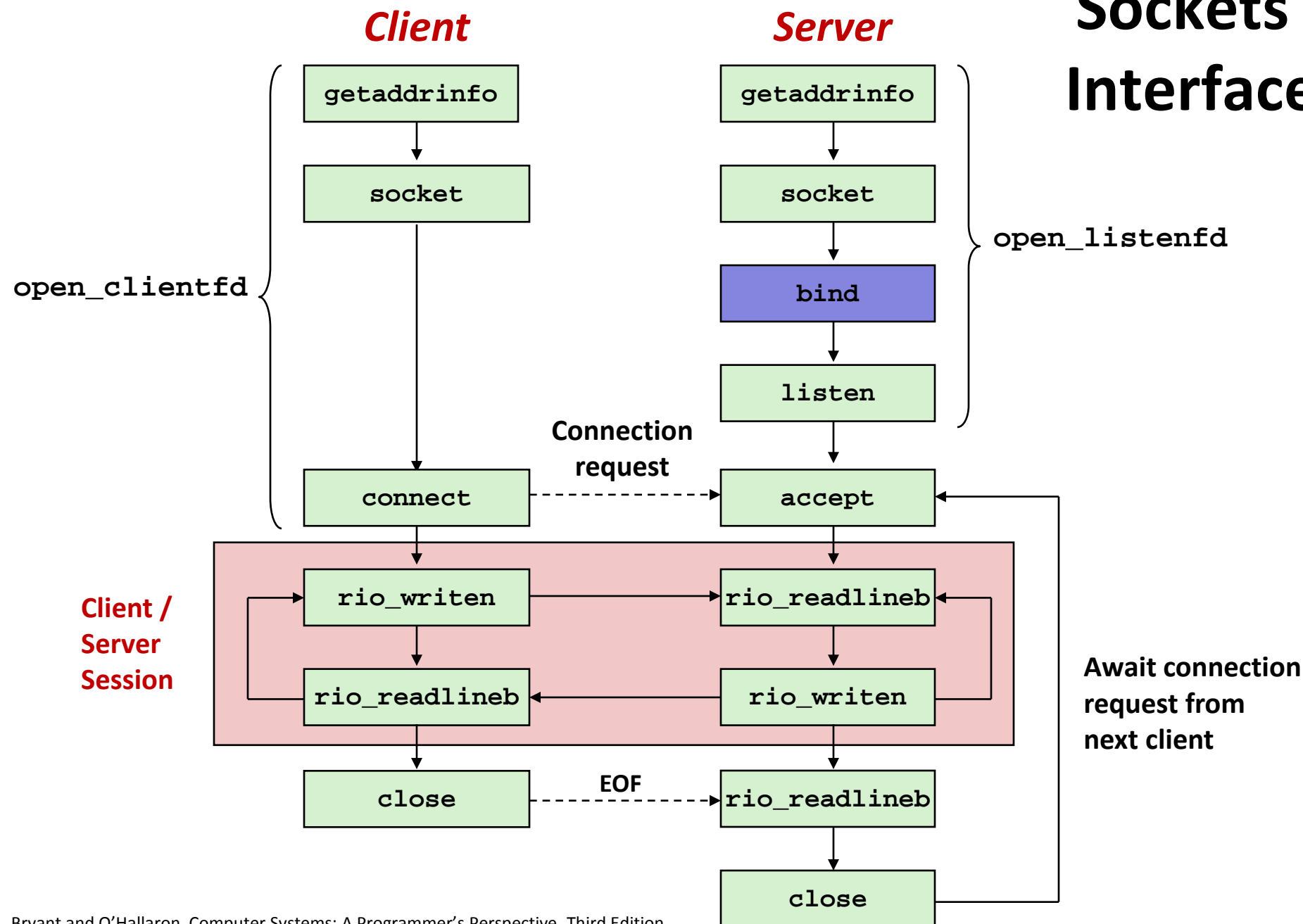
```
int clientfd = Socket(AF_INET, SOCK_STREAM, 0);
```

Indicates that we are using  
32-bit IPV4 addresses

Indicates that the socket  
will be the end point of a  
connection

Protocol specific! Best practice is to **use `getaddrinfo` to generate the parameters automatically**, so that code is protocol independent.

# Sockets Interface



# Sockets Interface: `bind`

- A server uses `bind` to ask the kernel to associate the server's socket address with a socket descriptor:

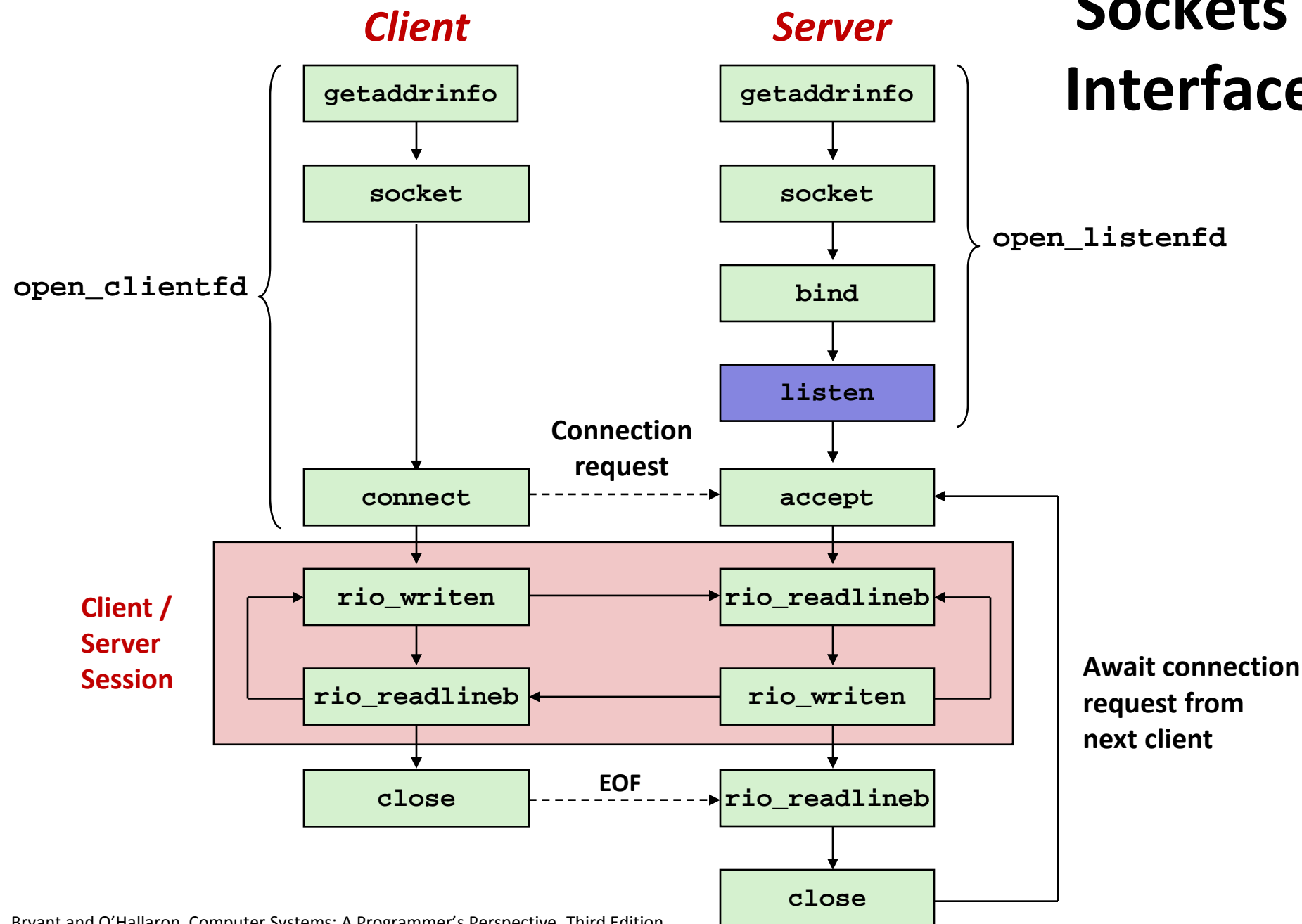
```
int bind(int sockfd, SA *addr, socklen_t addrlen);
```

- The process can read bytes that arrive on the connection whose endpoint is `addr` by reading from descriptor `sockfd`.
- Similarly, writes to `sockfd` are transferred along connection whose endpoint is `addr`.

Best practice is to **use `getaddrinfo` to supply the arguments `addr` and `addrlen`.**



# Sockets Interface



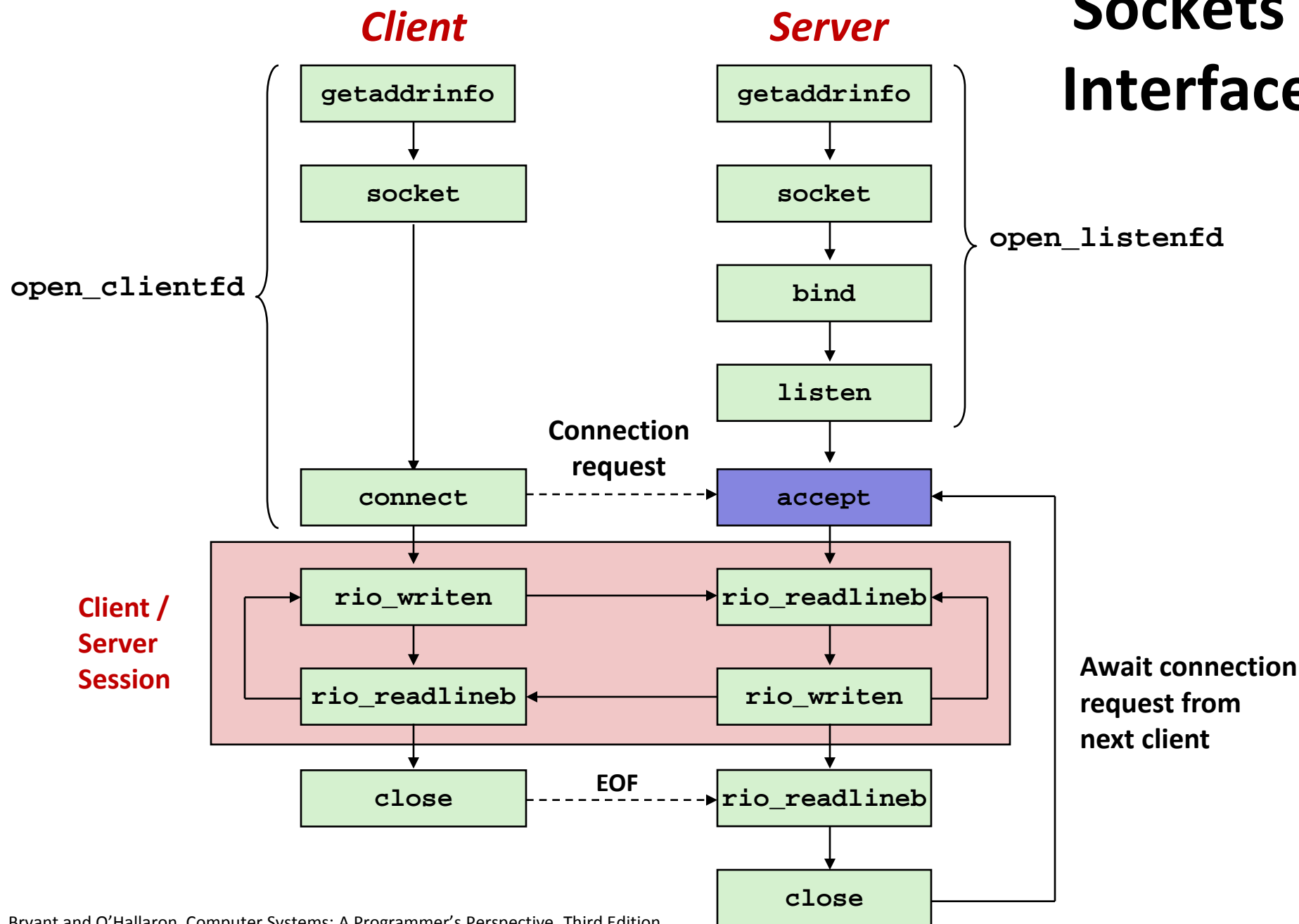
# Sockets Interface: `listen`

- By default, kernel assumes that descriptor from `socket` function is an *active socket* that will be on the client end of a connection.
- A server calls the `listen` function to tell the kernel that a descriptor will be used by a server rather than a client:

```
int listen(int sockfd, int backlog);
```

- Converts `sockfd` from an active socket to a *listening socket* that can accept connection requests from clients.
- `backlog` is a hint about the number of outstanding connection requests that the kernel should queue up before starting to refuse requests.

# Sockets Interface



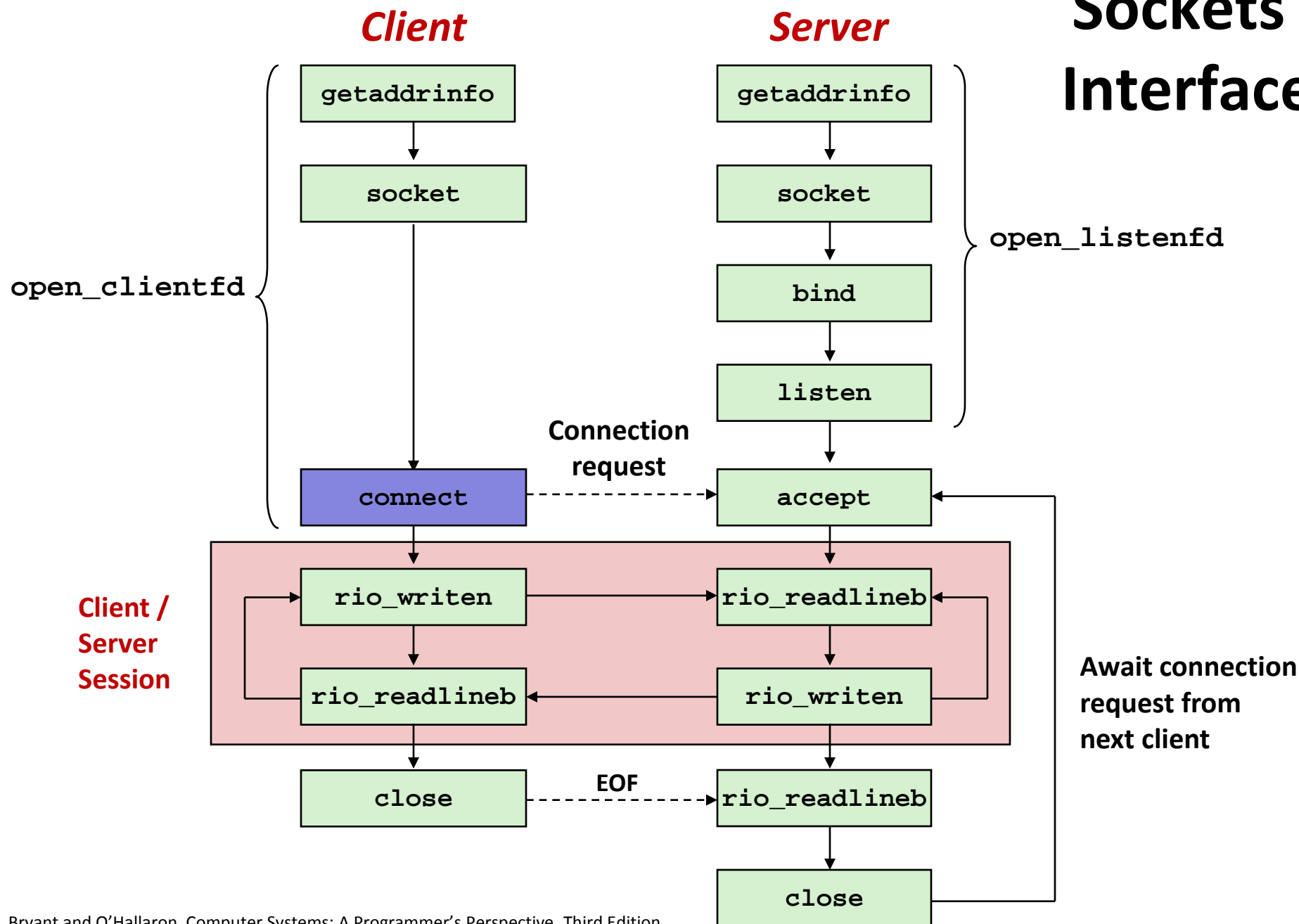
# Sockets Interface: `accept`

- Servers wait for connection requests from clients by calling `accept`:

```
int accept(int listenfd, SA *addr, int *addrlen);
```

- Waits for connection request to arrive on the connection bound to `listenfd`, then fills in client's socket address in `addr` and size of the socket address in `addrlen`.
- Returns a *connected descriptor* that can be used to communicate with the client via Unix I/O routines.

# Sockets Interface



# Sockets Interface: connect

- A client establishes a connection with a server by calling `connect`:

```
int connect(int clientfd, SA *addr, socklen_t addrlen);
```

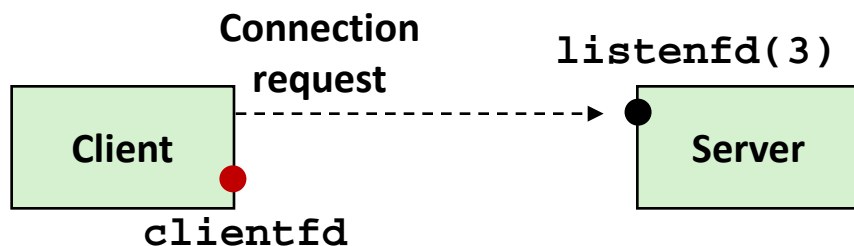
- Attempts to establish a connection with server at socket address `addr`
  - If successful, then `clientfd` is now ready for reading and writing.
  - Resulting connection is characterized by socket pair `(x:y, addr.sin_addr:addr.sin_port)`
    - `x` is client address
    - `y` is ephemeral port that uniquely identifies client process on client host

**Best practice is to use `getaddrinfo` to supply the arguments `addr` and `addrlen`.**

# accept Illustrated



*1. Server blocks in `accept`, waiting for connection request on listening descriptor `listenfd`*



*2. Client makes connection request by calling and blocking in `connect`*



*3. Server returns `connfd` from `accept`. Client returns from `connect`. Connection is now established between `clientfd` and `connfd`*

# Connected vs. Listening Descriptors

## ■ Listening descriptor

- End point for client connection requests
- Created once and exists for lifetime of the server

## ■ Connected descriptor

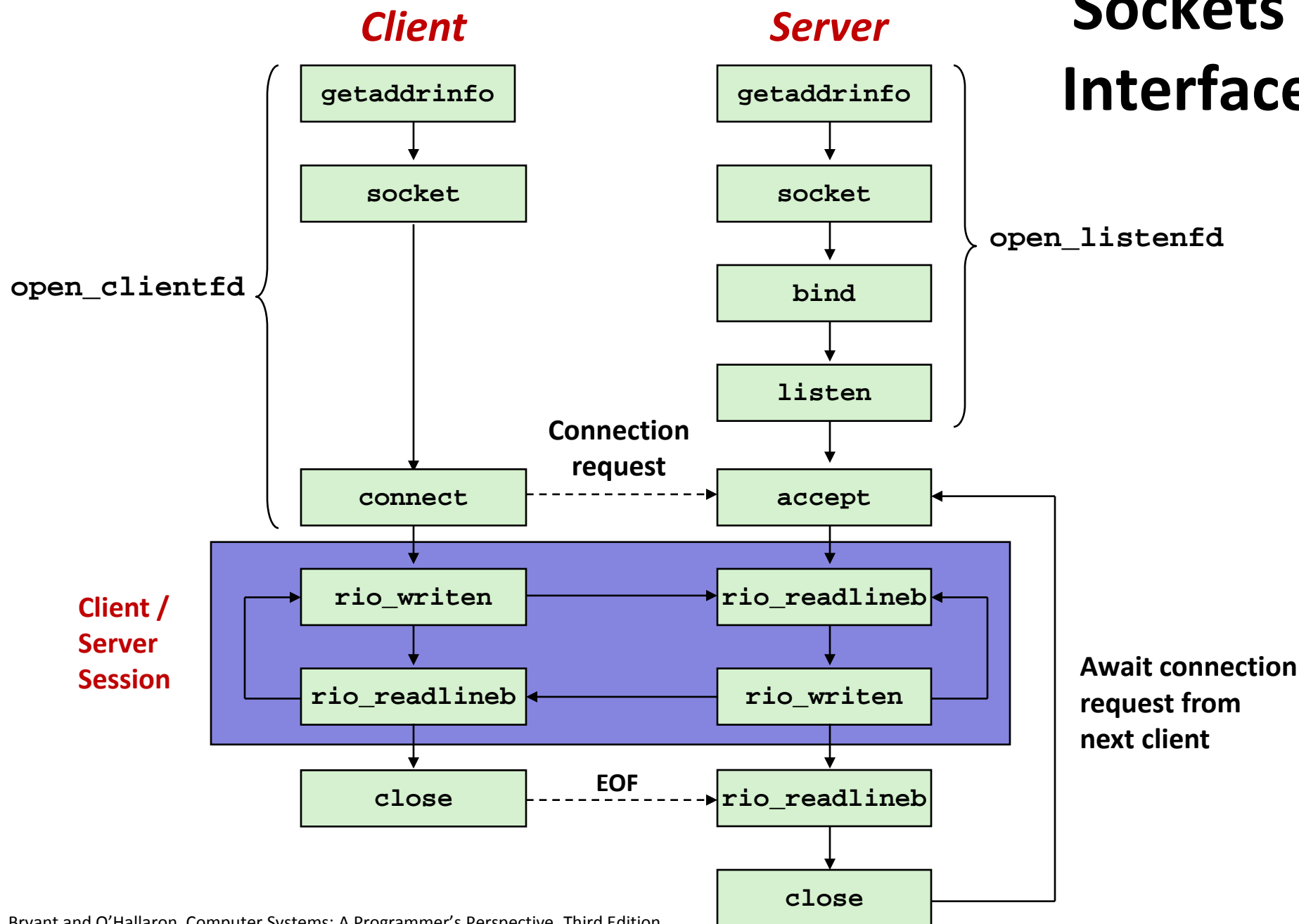
- End point of the connection between client and server
- A new descriptor is created each time the server accepts a connection request from a client
- Exists only as long as it takes to service client

## ■ Why the distinction?

- Allows for concurrent servers that can communicate over many client connections simultaneously
  - E.g., Each time we receive a new request, we fork a child to handle the request



# 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 cases.

# Host and Service Conversion: getaddrinfo

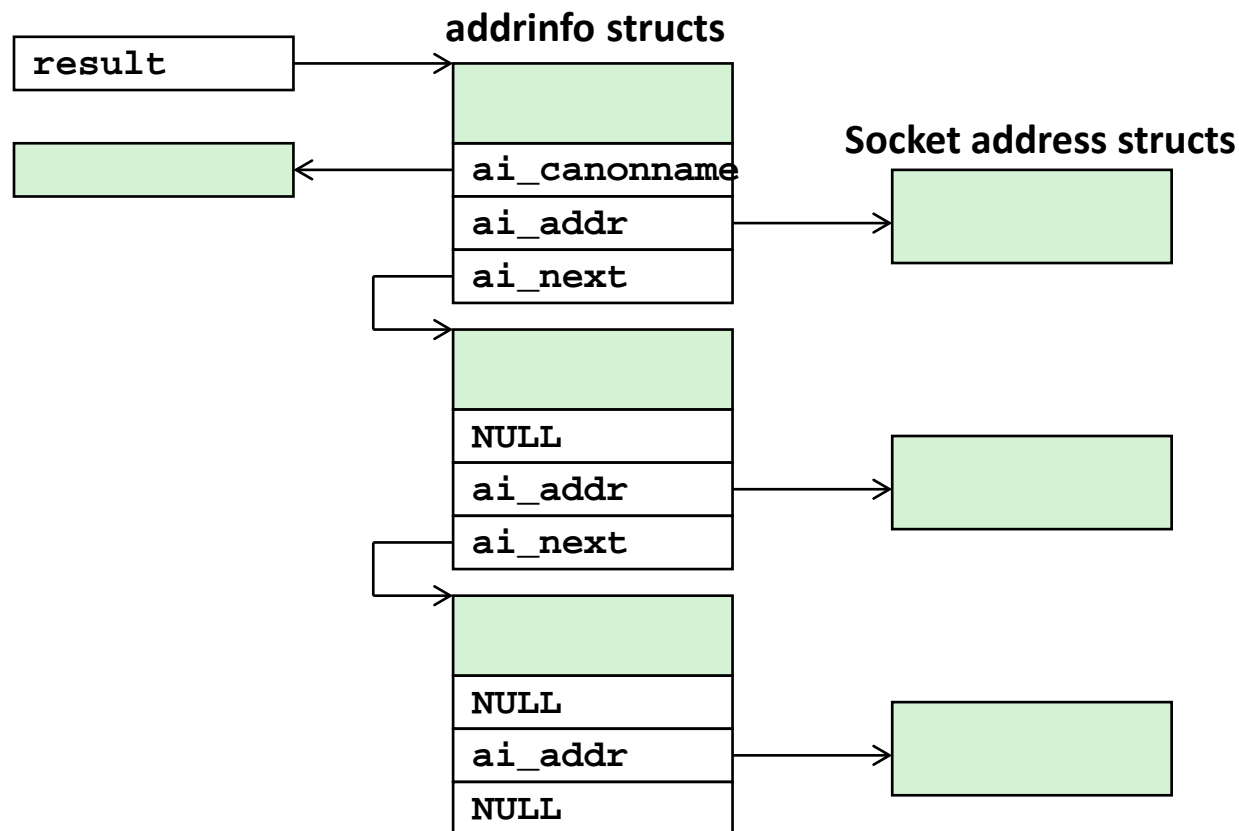
```
int getaddrinfo(const char *host,          /* Hostname or address */
               const char *service,       /* Port or service name
*/
               const struct addrinfo *hints, /* Input parameters */
               struct addrinfo **result);   /* Output linked list */

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!

# Additional slides

# 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)

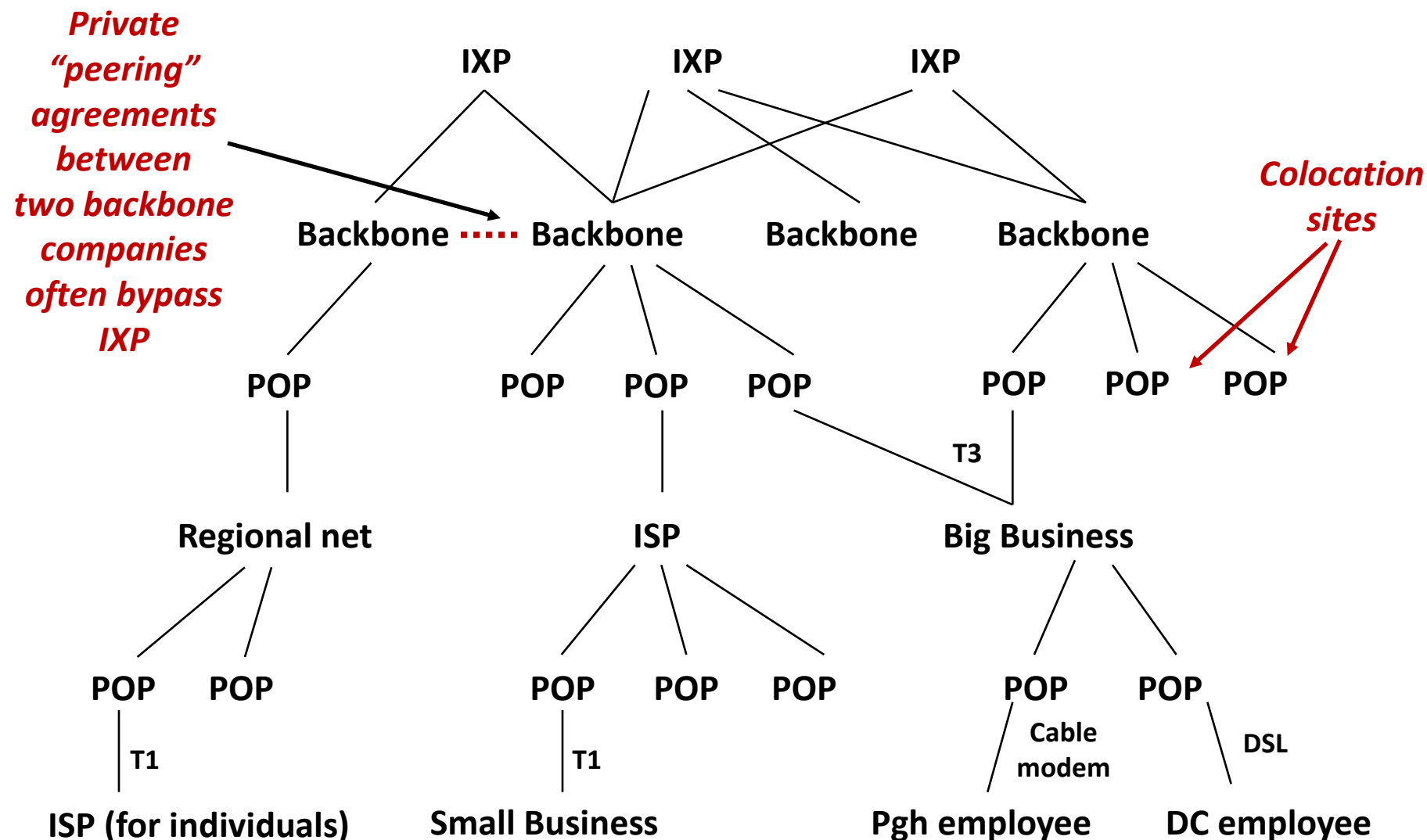
## ■ Point of presence (POP):

- 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:

	0	1	2	3	8	16	24	31																								
Class A	0	Net ID				Host ID																										
Class B	1	0	Net ID								Host ID																					
Class C	1	1	0	Net ID																		Host ID										
Class D	1	1	1	0	Multicast address																											
Class E	1	1	1	1	Reserved for experiments																											

## ■ 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

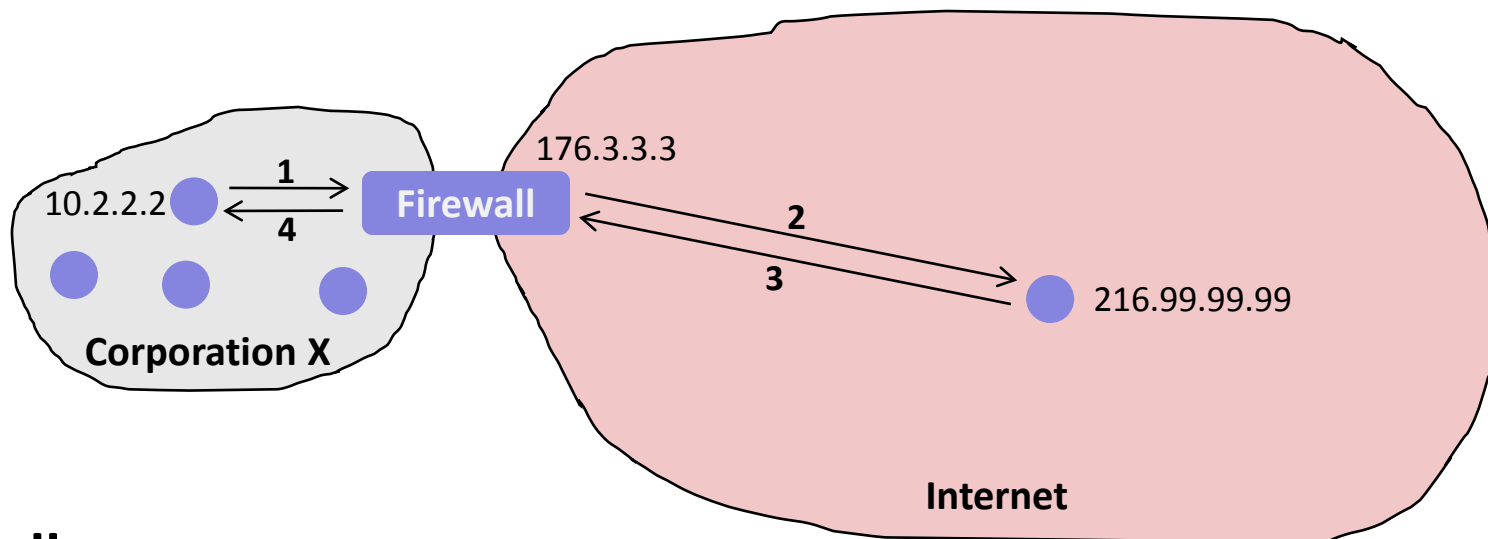
- Most hosts don't need to have known address
  - Only those functioning as servers
- DHCP (Dynamic Host Configuration Protocol)
  - Local ISP assigns address for temporary use

## ■ 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