Network Programming

Introduction to Computer Systems
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The Notion of an internet Protocol

Human protocols:

- **“what’s the time?”**
- **“I have a question”**
- **introductions**

Network protocols:

- **computers (devices) rather than humans**
- **all communication activity in Internet governed by protocols**

- **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

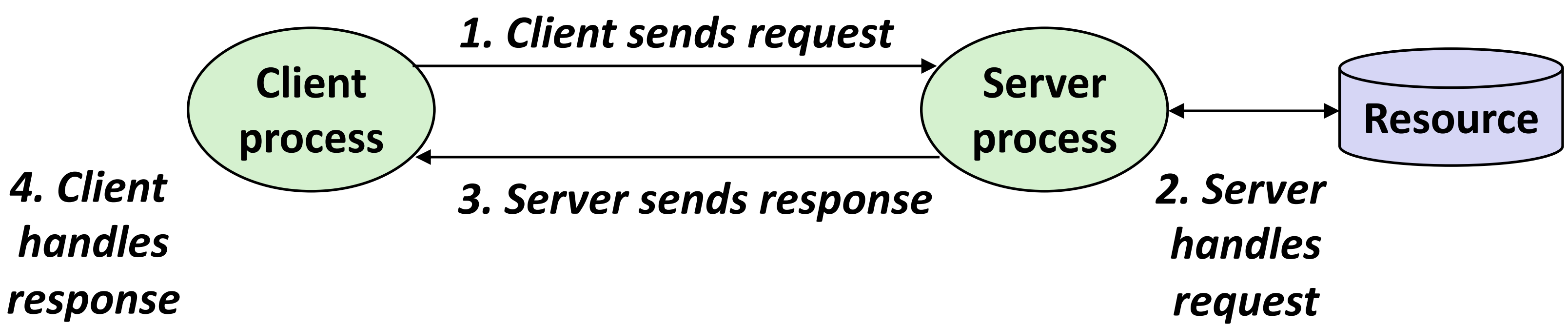
What Does an internet Protocol Do?

- **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

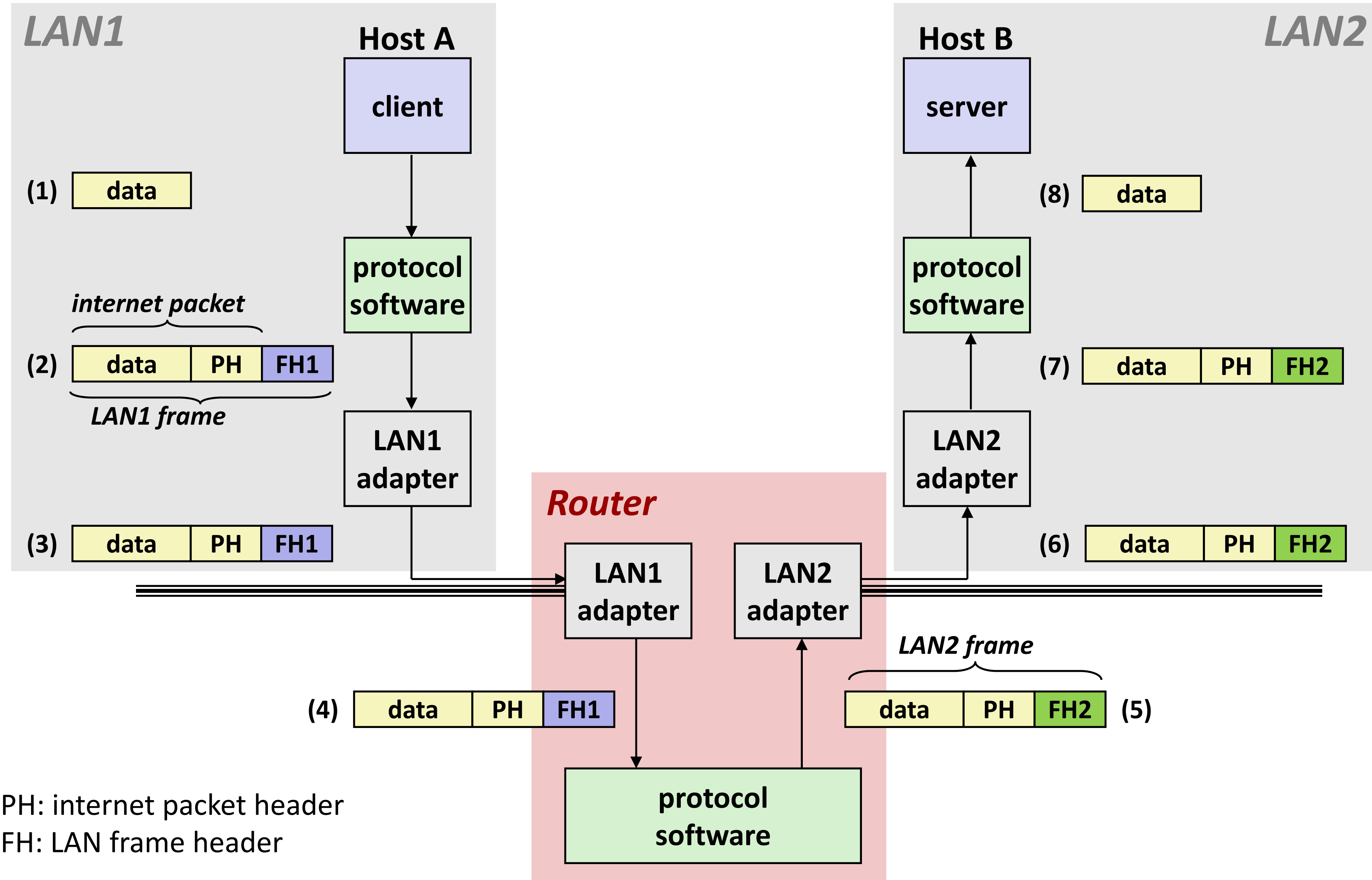
A Client-Server Transaction

- **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)

Transferring internet Data Via Encapsulation



PH: internet packet header
FH: LAN frame header

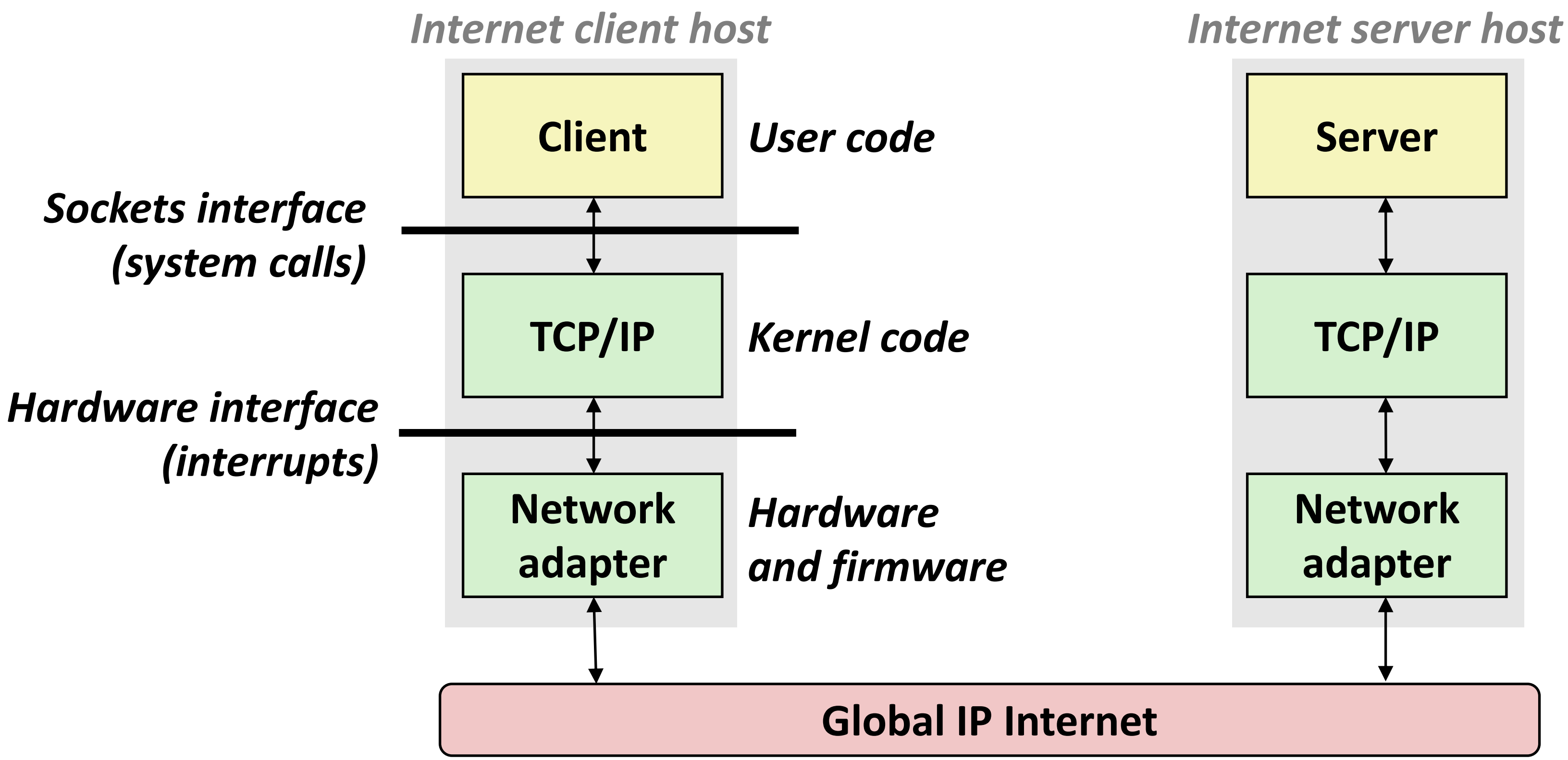
Global IP Internet (upper case)

- **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
- 127.0.0.1 (always *localhost*)

2. As a convenience for humans, the Domain Name System maps a set of identifiers called Internet *domain names* to IP addresses:

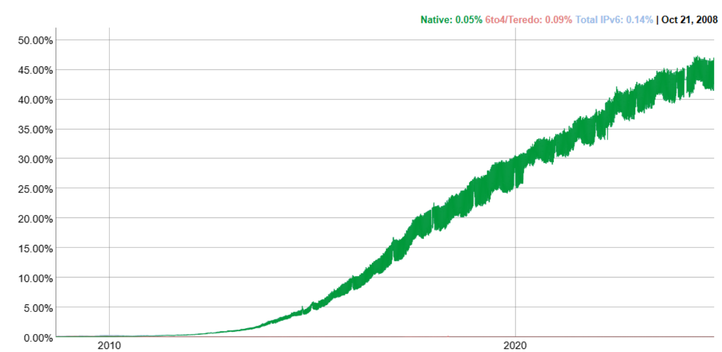
- 128.2.217.3 is mapped to www.cs.cmu.edu
- www.cs.cmu.edu "resolves to" 128.2.217.3

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

Aside: IPv4 and IPv6

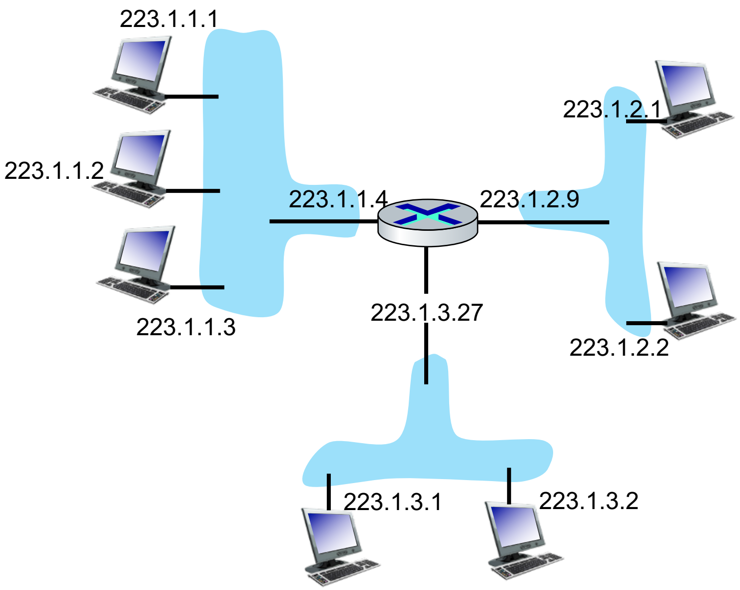
- **IPv4 (*Internet Protocol Version 4*) specified 1981**
  - 32-bit host addresses
  - Known to not be enough for everyone since ~1990
  - Majority of Internet traffic still carried by IPv4
- **IPv6 (*Internet Protocol Version 6*) specified 1996**
  - 128-bit addresses (2001:0db8:0:0:0:0:cafe:1a7e)
  - Intended to replace IPv4
  - Very slow adoption due to need to replace routers
- **Application programmers mostly don't have to care**
  - Sockets API makes it easy to write code that seamlessly uses either, as necessary

IPv6 traffic to Google
https://www.google.com/intl/en/ipv6/statistics.html



(1) IP Addresses

- **IP address: 32-bit identifier associated with each host or router *interface***
- **interface: connection between host/router and physical link**
  - router's typically have multiple interfaces
  - host typically has one or two interfaces (e.g., wired Ethernet, wireless 802.11)

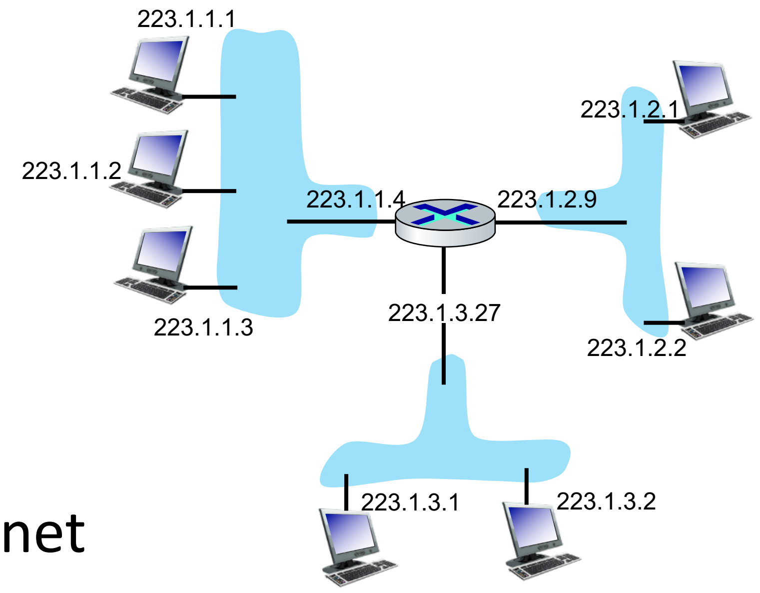


dotted-decimal IP address notation:

$$223.1.1.1 = \underbrace{11011111}_{223}\ \underbrace{00000001}_{1}\ \underbrace{00000001}_{1}\ \underbrace{00000001}_{1}$$

Subnets

- *What's a subnet ?*
  - device interfaces that can physically reach each other without passing through an intervening router
- IP addresses have structure:
  - subnet part: devices in same subnet have common high order bits
  - host part: remaining low order bits

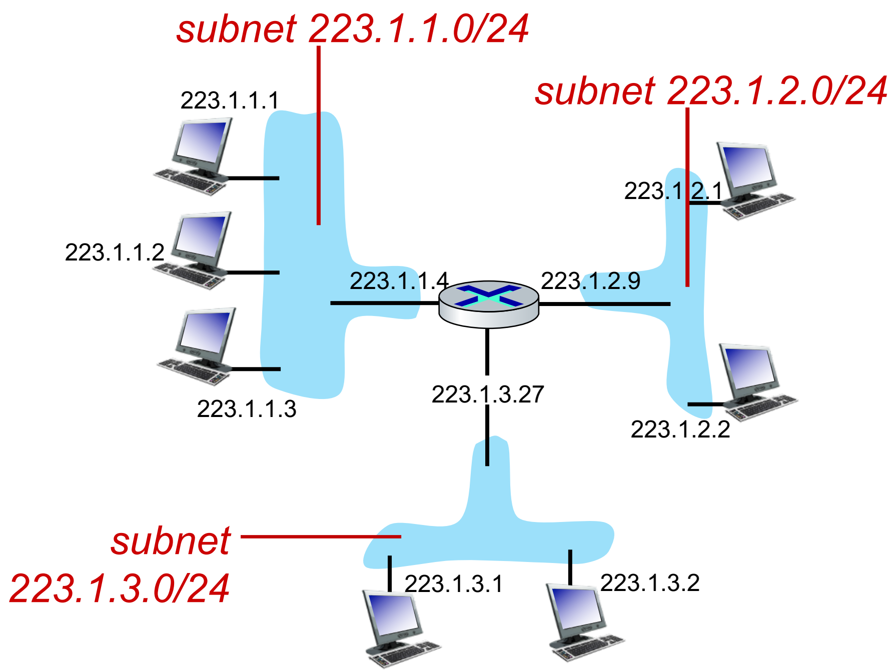


network consisting of 3 subnets

Subnets

Recipe for defining subnets:

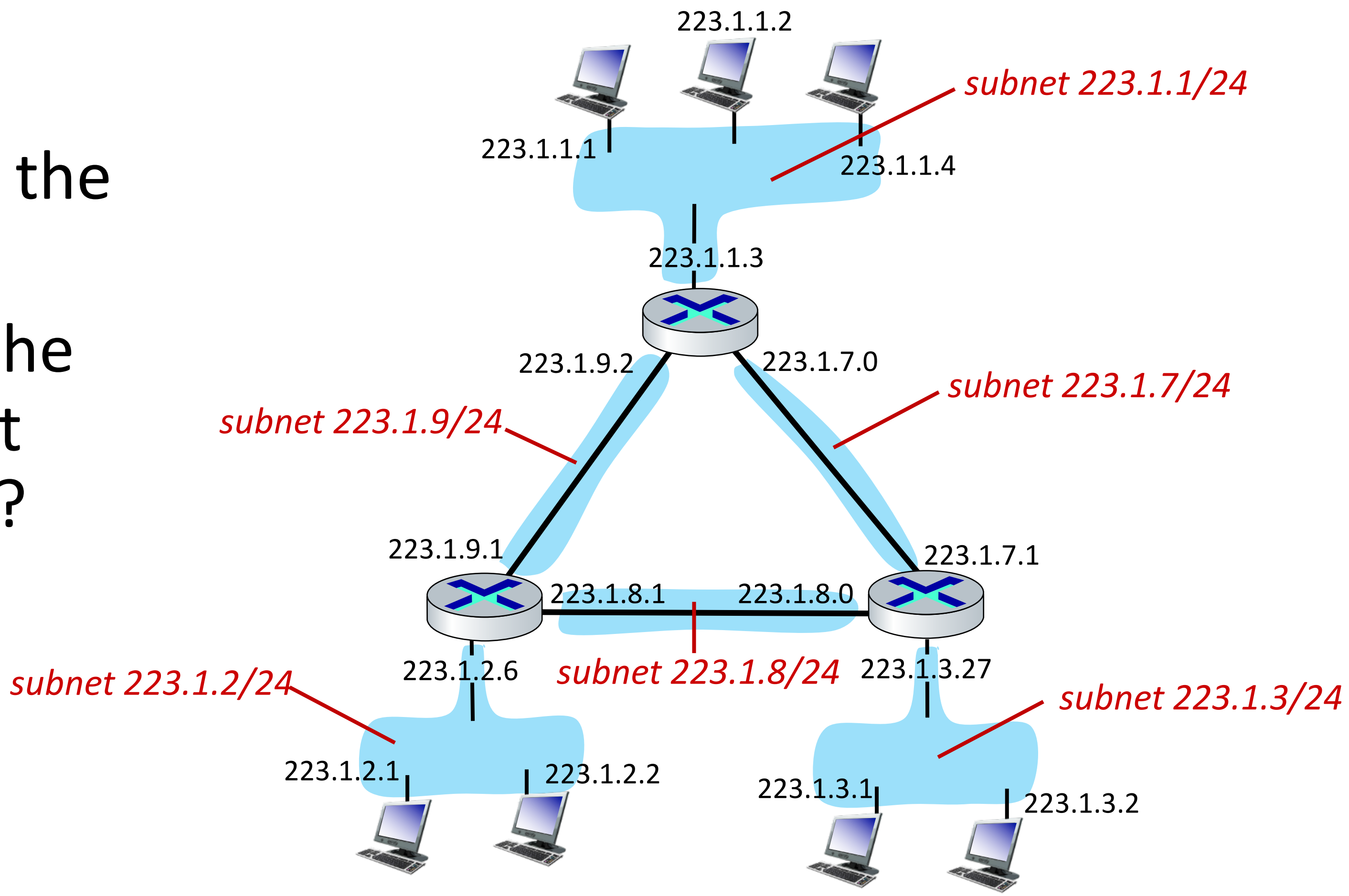
- detach each interface from its host or router, creating "islands" of isolated networks
- each isolated network is called a *subnet*



subnet mask: /24
(high-order 24 bits: subnet part of IP address)

Subnets

- where are the subnets?
- what are the /24 subnet addresses?



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

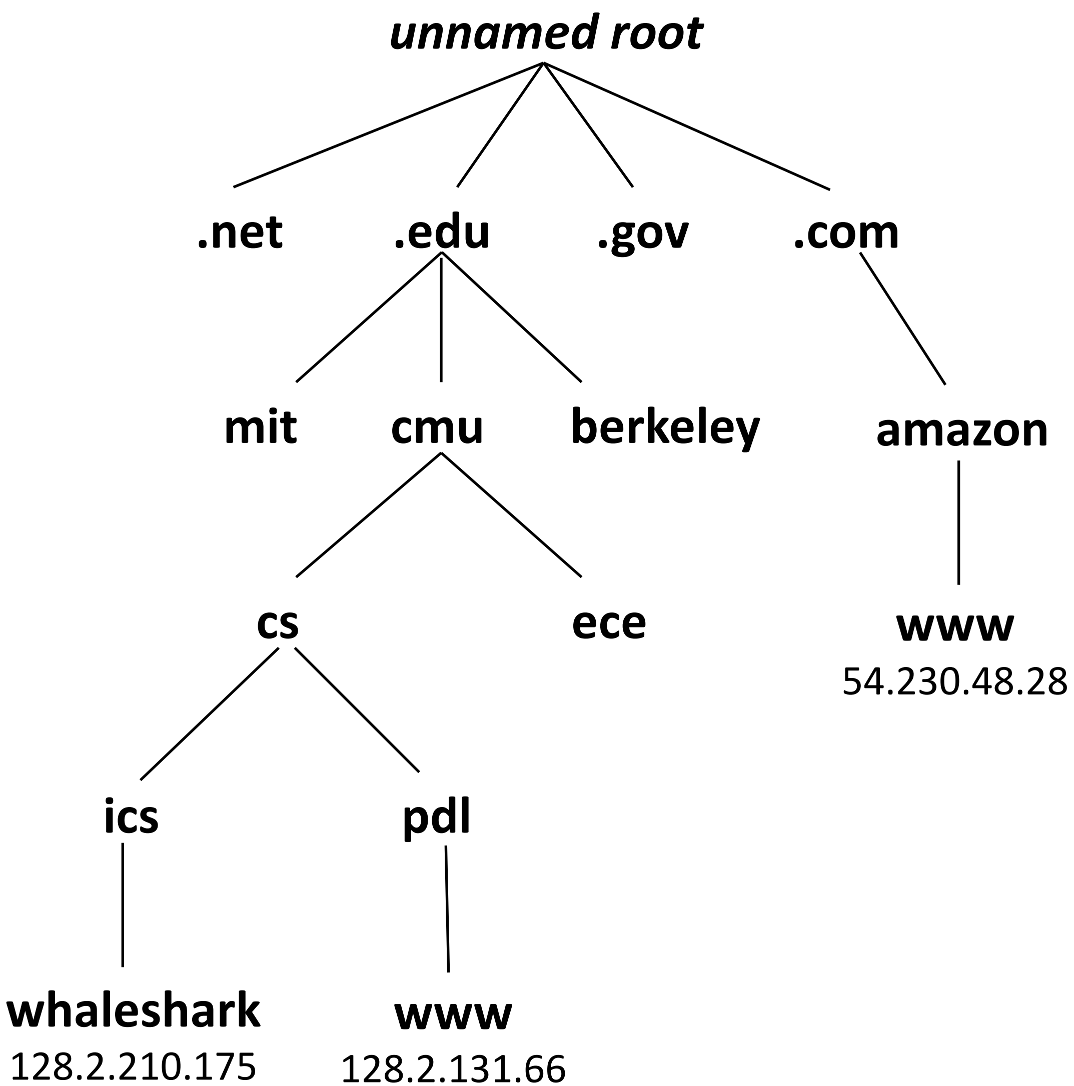
IP Addresses

- **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) */
};
```

- **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`

(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: 18.25.0.23
linux> nslookup eecs.mit.edu
Address: 18.25.0.23
```

- And backwards:

```
linux> nslookup 18.25.0.23
23.0.25.18.in-addr.apra    name = eecs.mit.edu.
```

Properties of DNS Mappings (cont)

- **Multiple domain names mapped to multiple IP addresses:**

```
linux> nslookup www.tencent.com
Address: 116.131.60.102
Address: 115.56.90.84
Address: 116.196.155.54
Address: 115.56.90.198
Address: 116.196.145.223

linux> nslookup www.tencent.com
Address: 116.196.155.54
Address: 116.196.145.223
Address: 115.56.90.84
Address: 116.131.60.102
Address: 115.56.90.198
```

- **Some valid domain names don't map to any IP address:**

```
linux> nslookup ics.cs.cmu.edu
(No Address given)
```

(3) Internet Connections

- **Clients and servers most often communicate by sending streams of bytes over TCP *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)

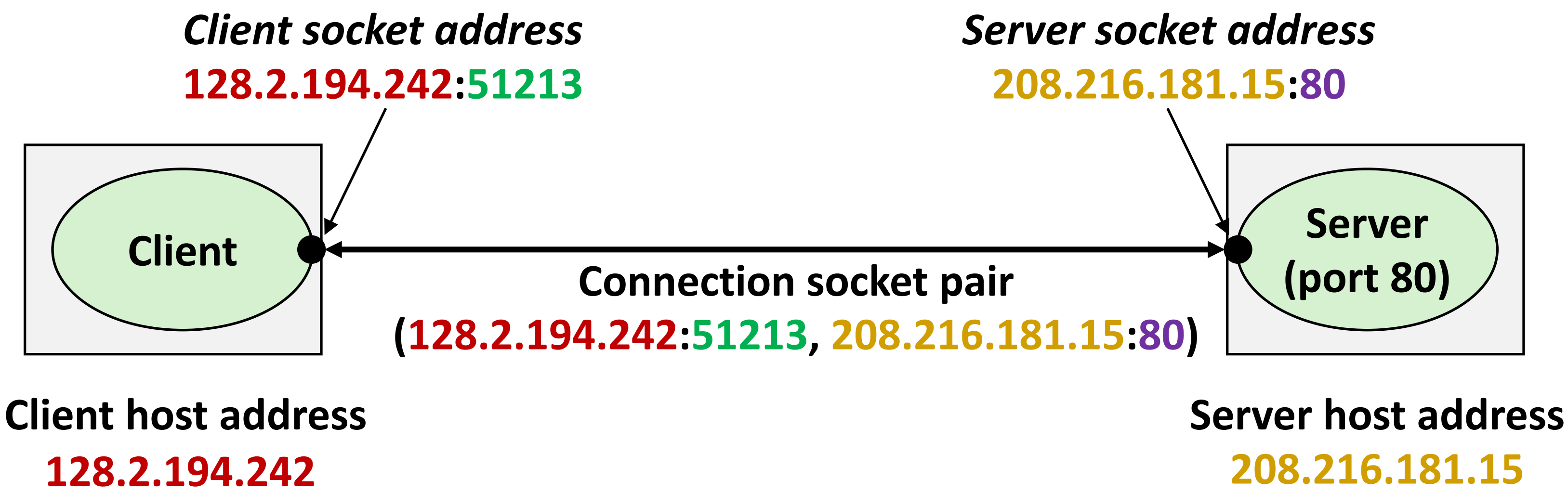
Well-known Service Names and Ports

- **Popular services have permanently assigned *well-known ports and* corresponding *well-known service names*:**
  - echo servers: echo 7
  - ftp servers: ftp 21
  - ssh servers: ssh 22
  - email servers: smtp 25
  - Unencrypted Web servers: http 80
  - SSL/TLS encrypted Web: https 443

- **Mappings between well-known ports and service names is contained in the file `/etc/services` on each Linux machine.**

Anatomy of a Connection

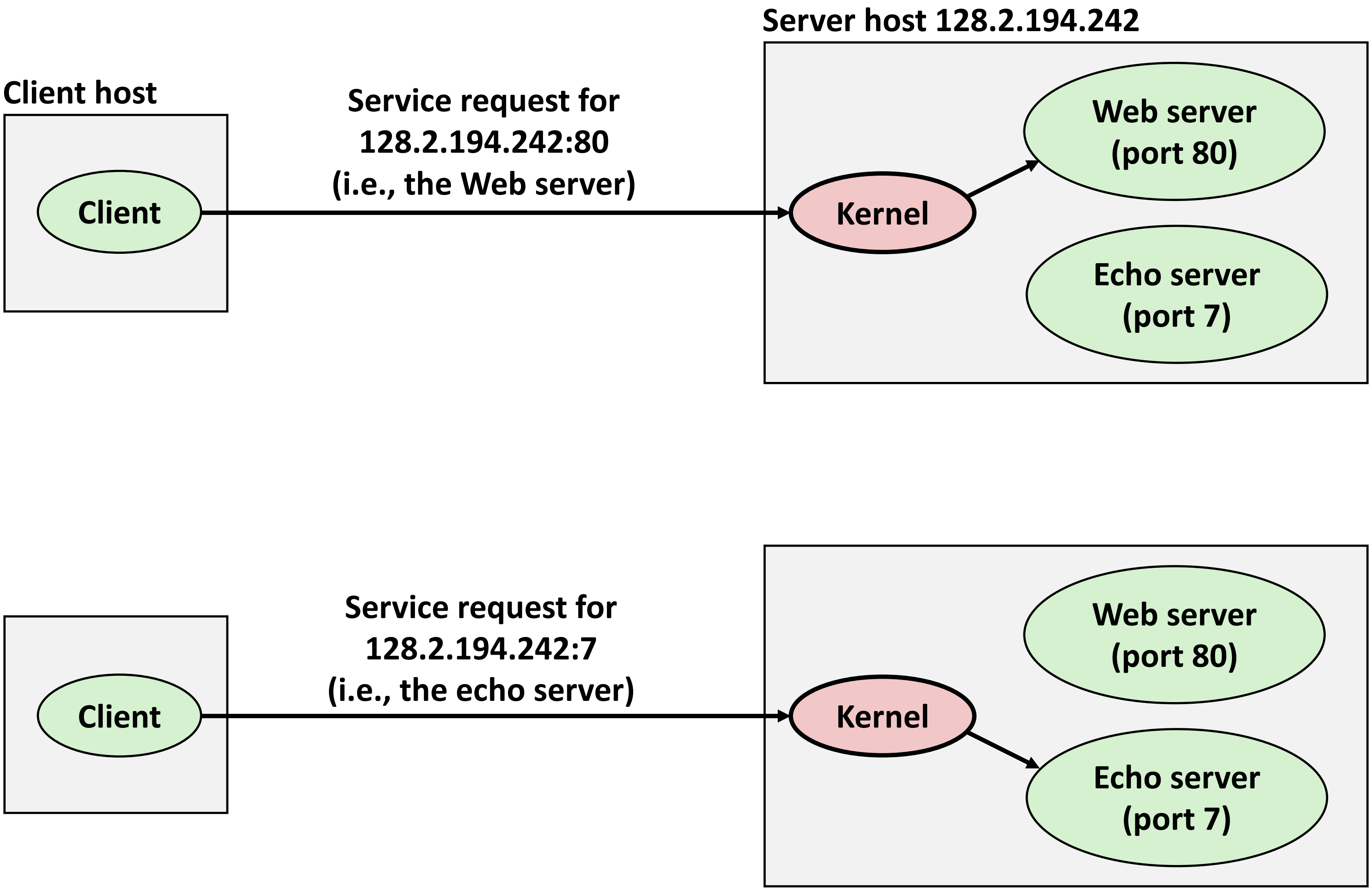
- A connection is uniquely identified by the socket addresses of its endpoints (*socket pair*)
  - `(cliaddr:cliport, servaddr:servport)`



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

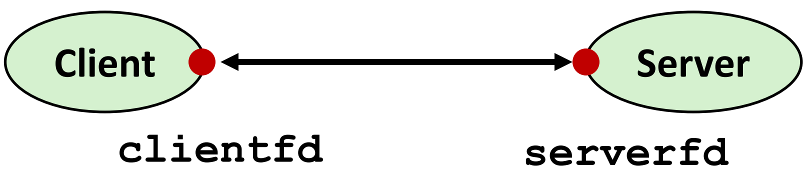
- **Set of system-level functions used in conjunction with Unix I/O to build network applications.**

- **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
  - Using the FD abstraction lets you reuse code & interfaces
    - ***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**



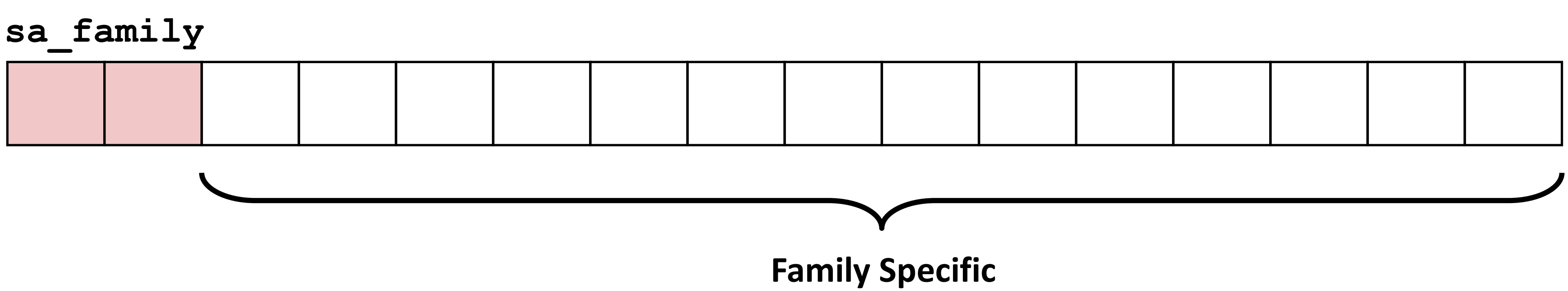
- **The main distinction between regular file I/O and socket I/O is how the application "opens" the socket descriptors**

Socket Address Structures

- **Generic socket address:**
  - For address arguments to **`connect`**, **`bind`**, and **`accept`** *(next lecture)*
  - 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;`

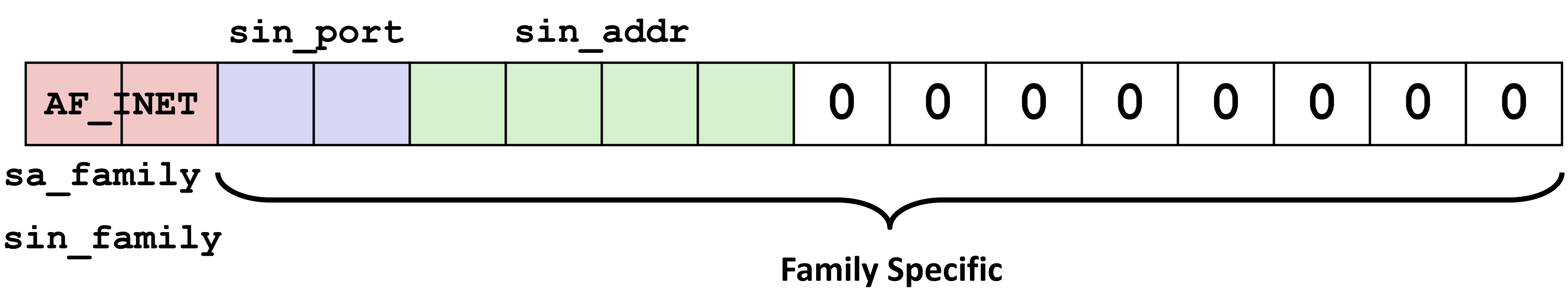
```
struct sockaddr {
  uint16_t  sa_family;    /* Protocol family */
  char      sa_data[14];  /* Address data  */
};
```



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

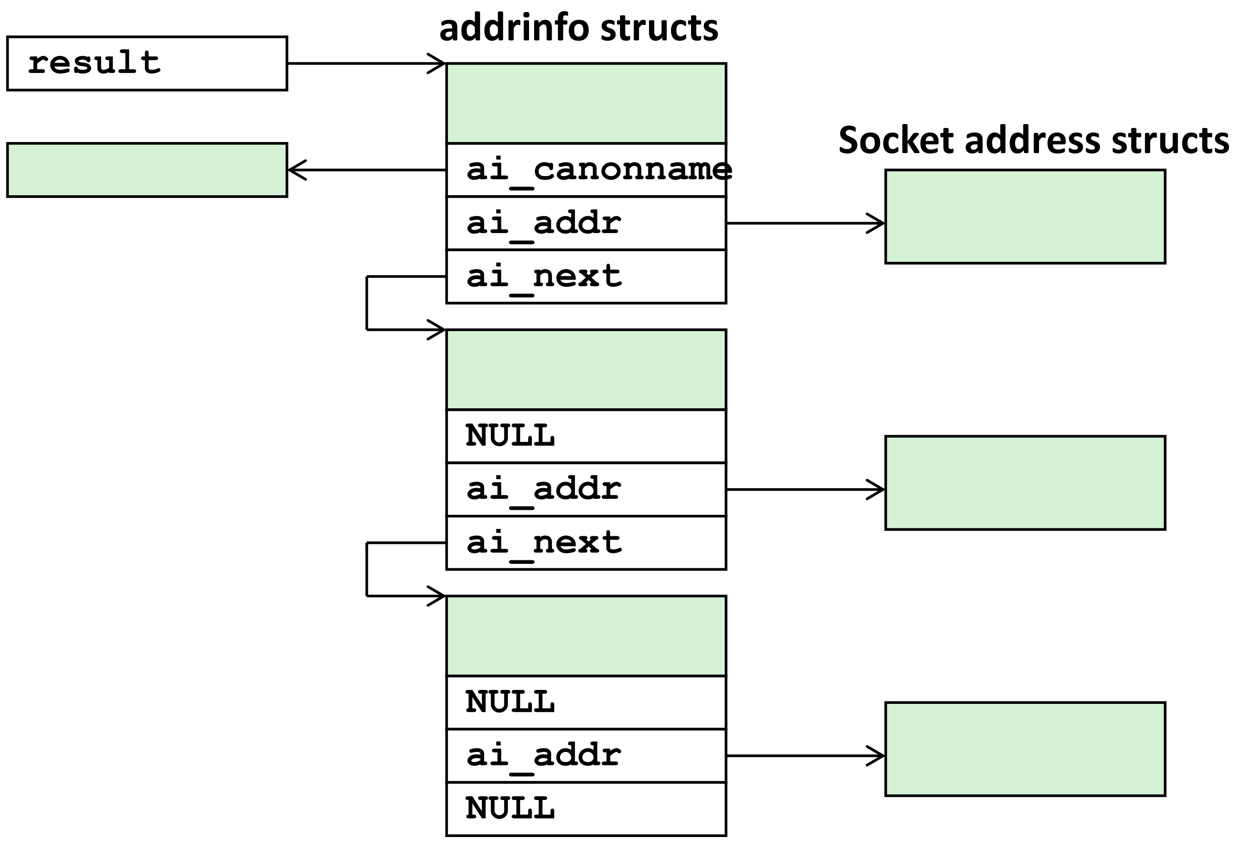
- **Disadvantages**
  - Somewhat complex
  - Fortunately, a small number of usage patterns suffice in most cases.

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:**
  - `freeadderinfo` frees the entire linked list.
  - `gai_strerror` converts error code to an error message.

Linked List Returned by `getaddrinfo`



`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

whaleshark> ./hostinfo google.com
172.217.15.110
2607:f8b0:4004:802::200e
```

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

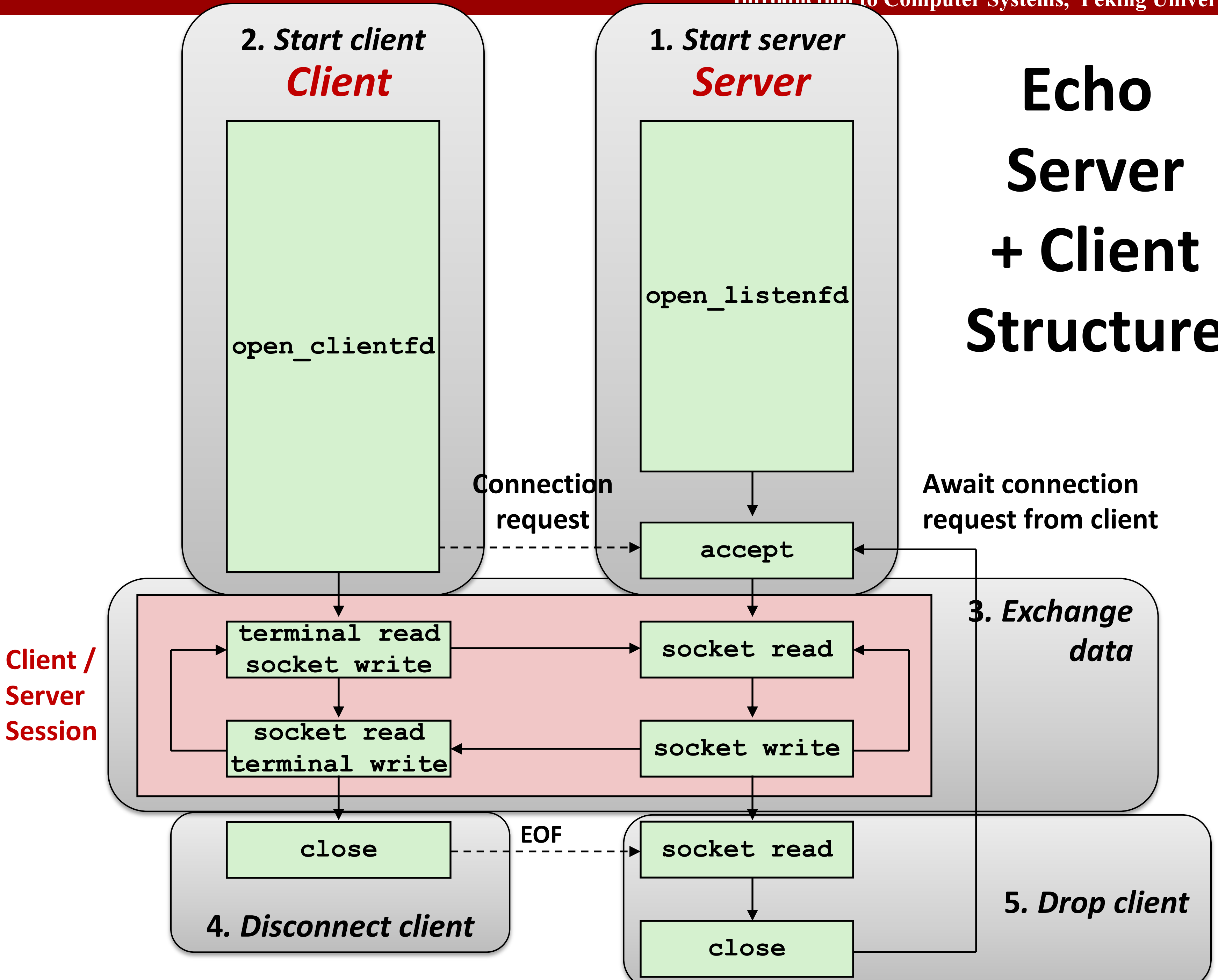
Client

```
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
```

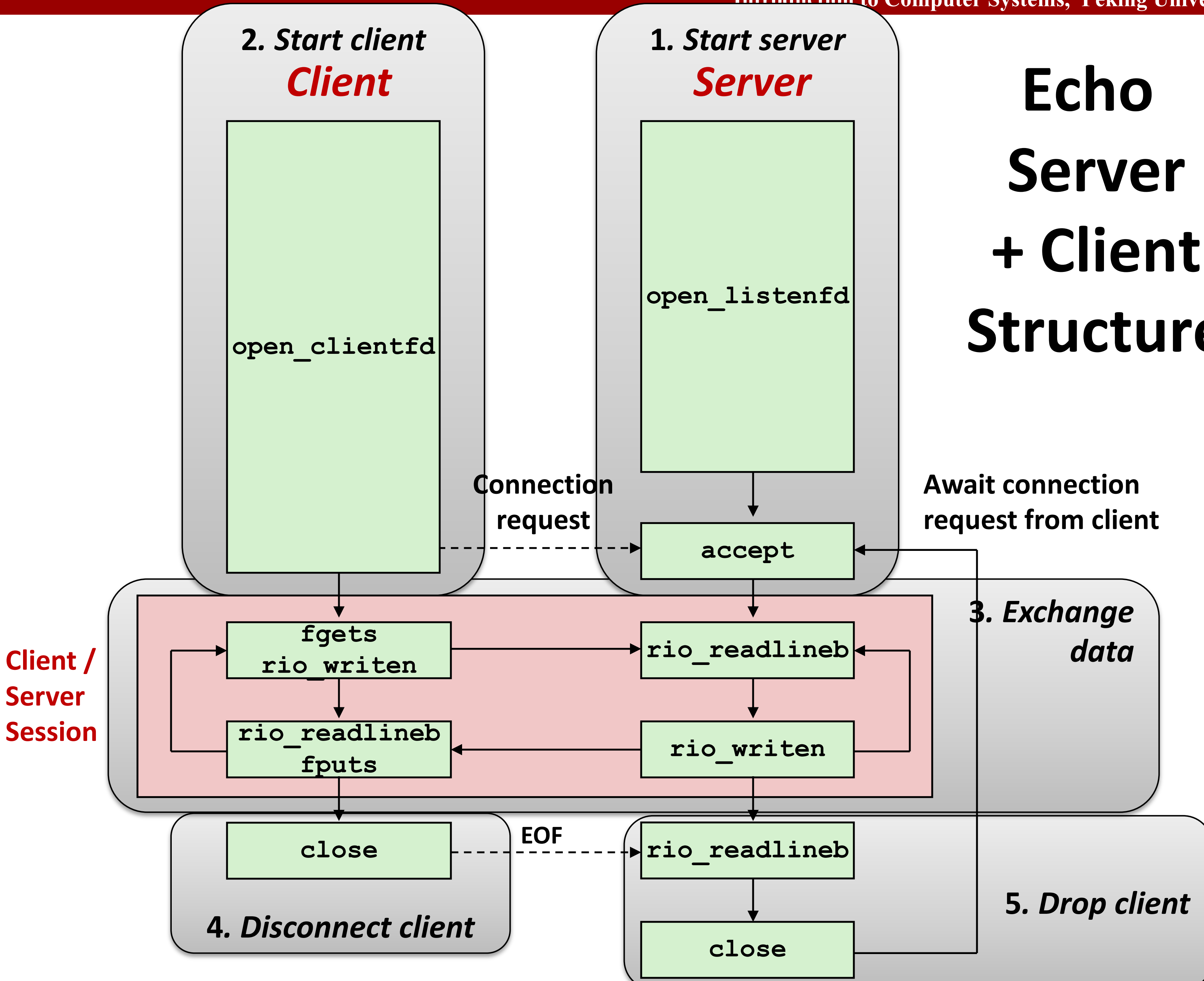
Server

```
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 Server + Client Structure



Echo Server + Client Structure



Recall: Unbuffered RIO Input/Output

- **Same interface as Unix `read` and `write`**
- **Especially useful for transferring data on network sockets**

```
#include "csapp.h"

ssize_t rio_readn(int fd, void *usrbuf, size_t n);
ssize_t rio_writen(int fd, void *usrbuf, size_t n);
```

Return: num. bytes transferred if OK, 0 on EOF (`rio_readn` only), -1 on error

- **`rio_readn`** returns short count only if it encounters EOF
  - Only use it when you know how many bytes to read
- **`rio_writen`** never returns a short count
- Calls to **`rio_readn`** and **`rio_writen`** can be interleaved arbitrarily on the same descriptor

Recall: Buffered RIO Input Functions

- **Efficiently read text lines and binary data from a file partially cached in an internal memory buffer**

```
#include "csapp.h"

void rio_readinitb(rio_t *rp, int fd);

ssize_t rio_readlineb(rio_t *rp, void *usrbuf, size_t maxlen);
ssize_t rio_readnb(rio_t *rp, void *usrbuf, size_t n);
```

Return: num. bytes read if OK, 0 on EOF, -1 on error

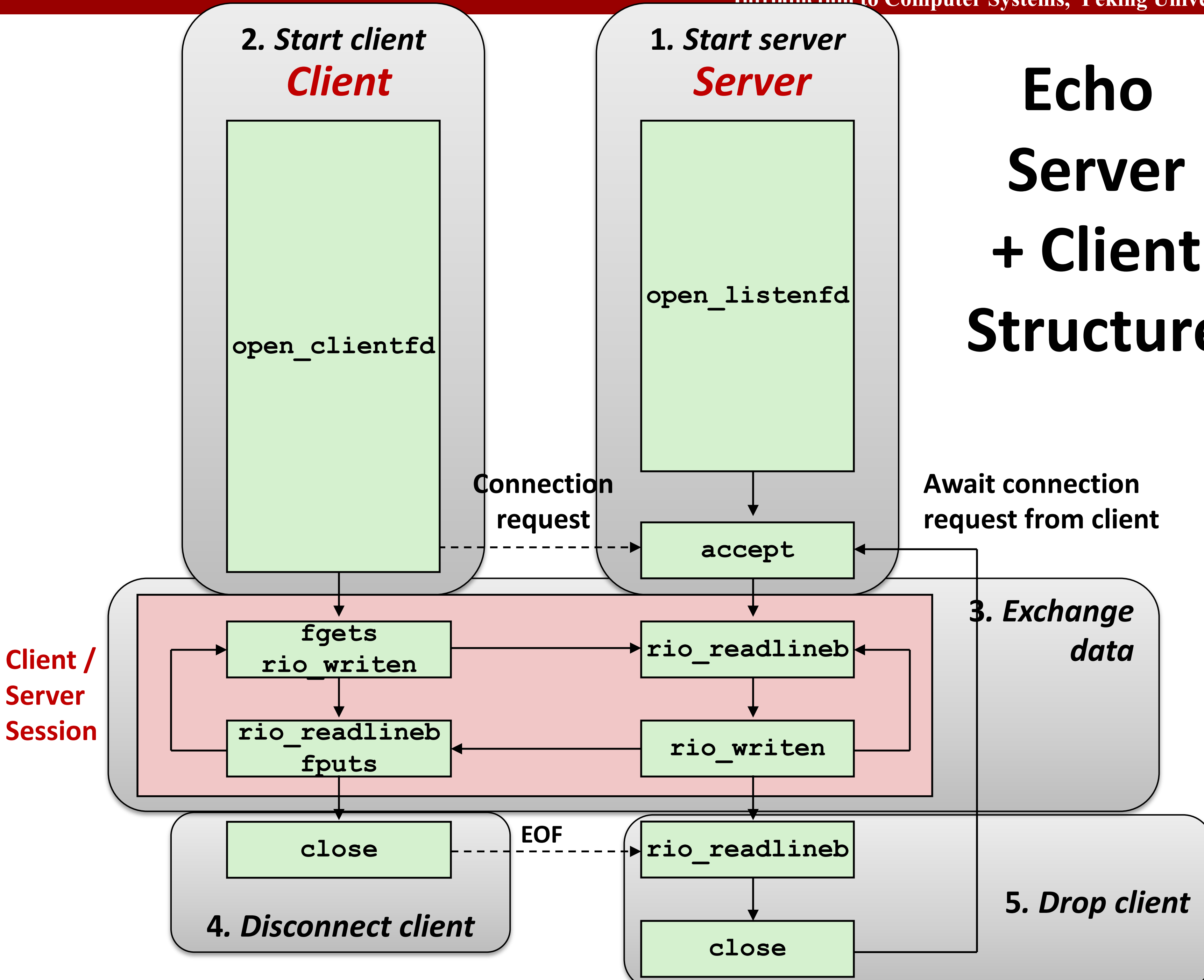
- `rio_readlineb` reads a *text line* of up to **`maxlen`** bytes from file **`fd`** and stores the line in **`usrbuf`**
  - Especially useful for reading text lines from network sockets
- Stopping conditions
  - **`maxlen`** bytes read
  - EOF encountered
  - Newline (‘**`\n`**’) encountered

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

Echo Server + Client Structure



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

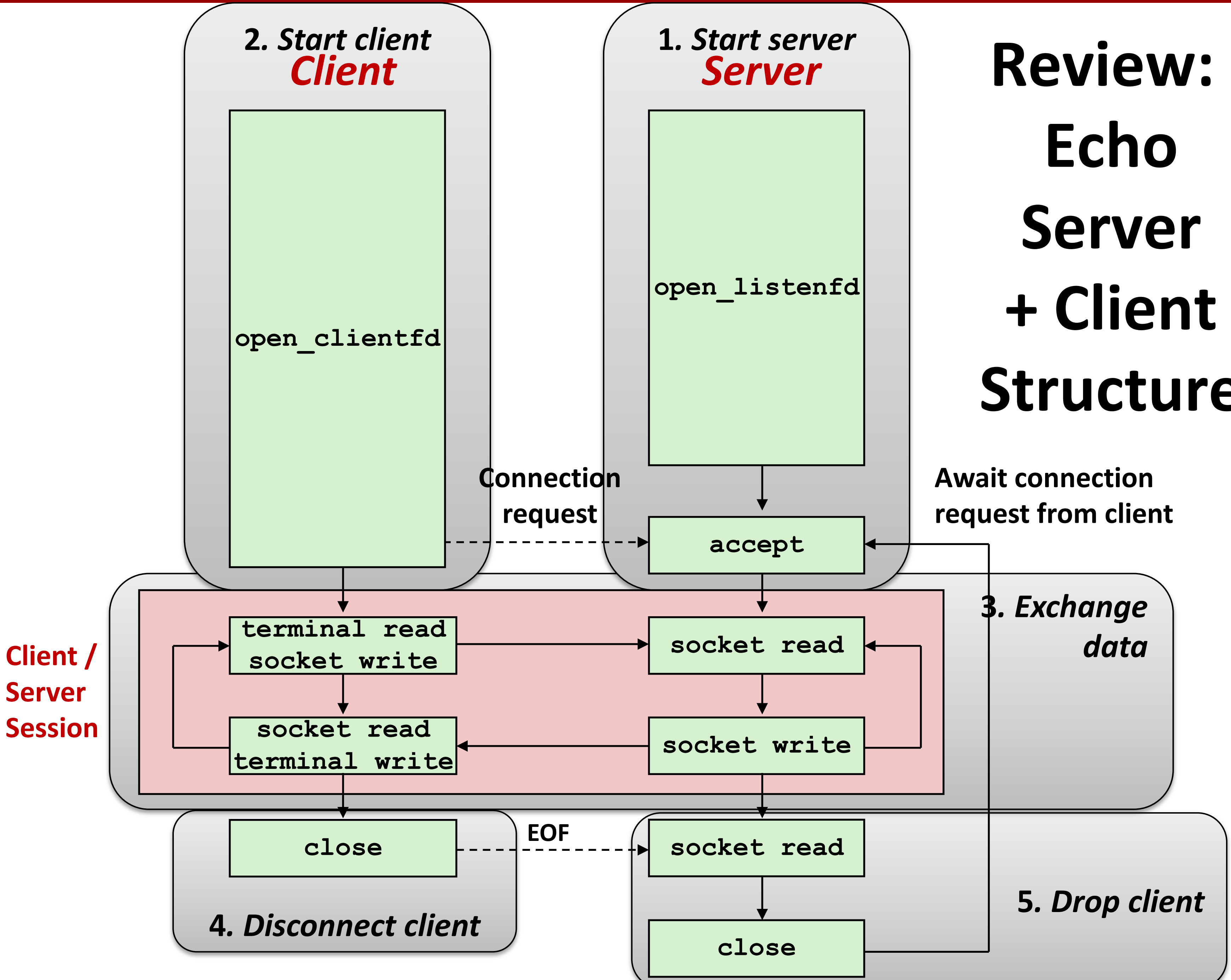
Echo Server: echo function

- **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)`

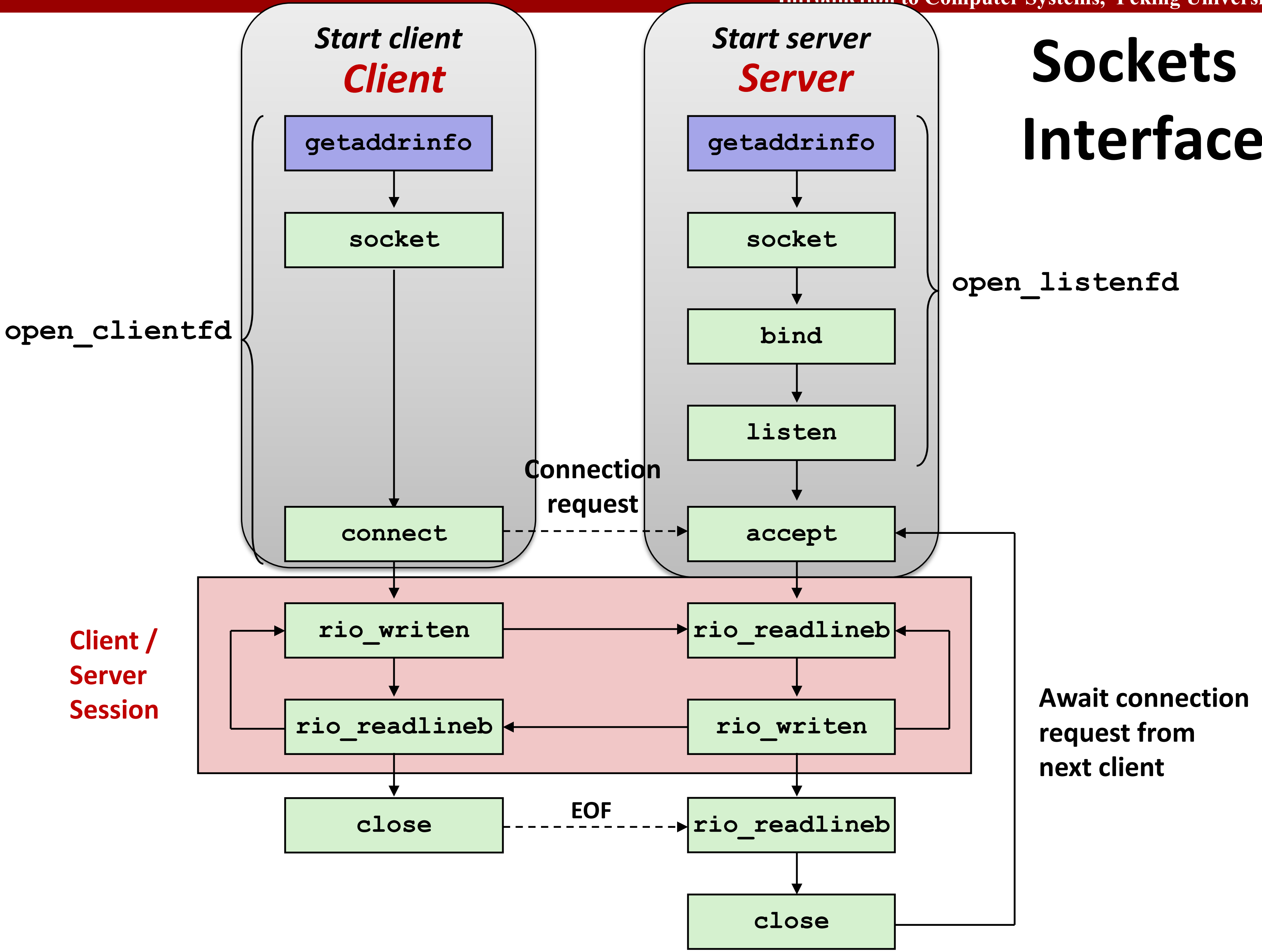
```c
void echo(int connfd)
{
    size_t n;
    char buf[MAXLINE];
    rio_t rio;

    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

Review: Echo Server + Client Structure

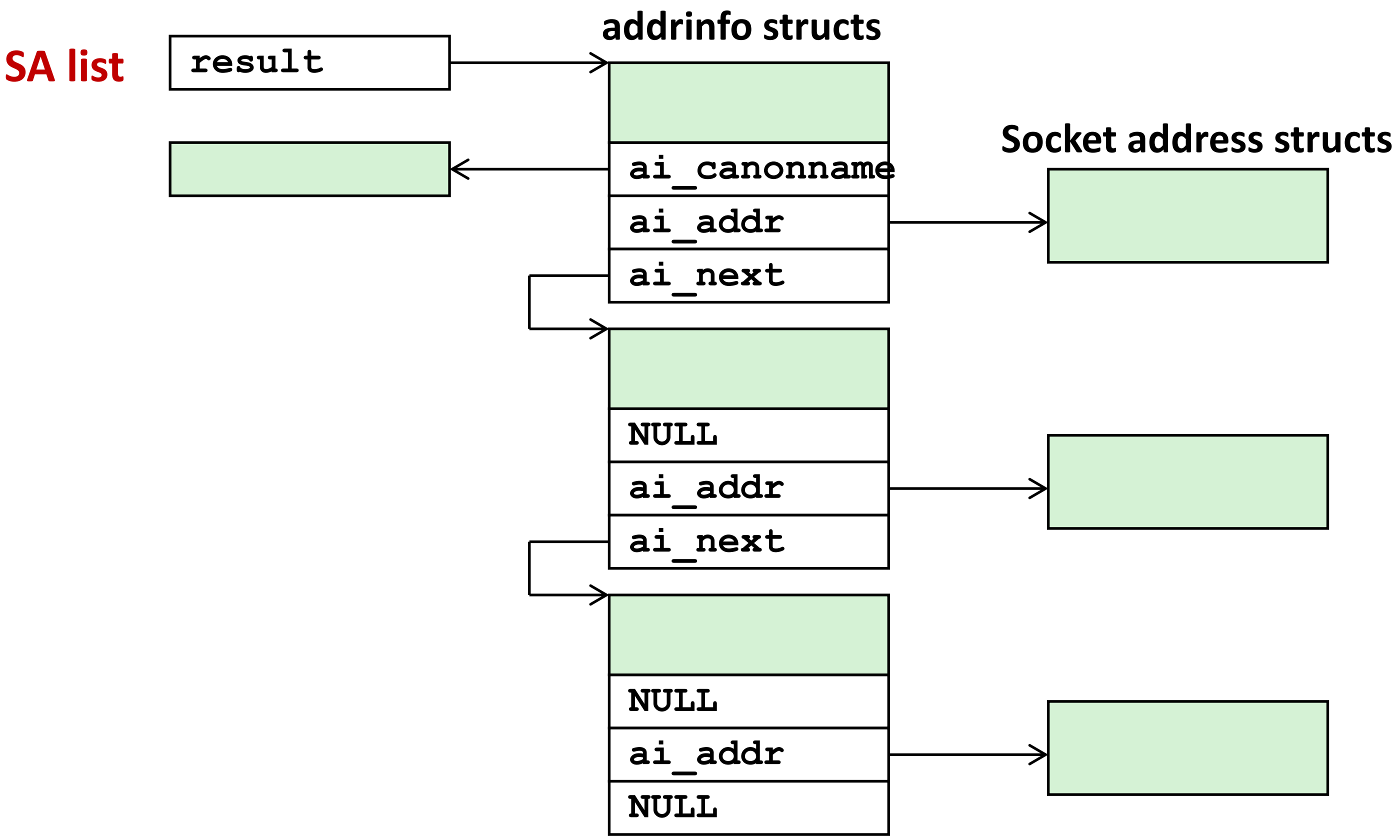


Sockets Interface

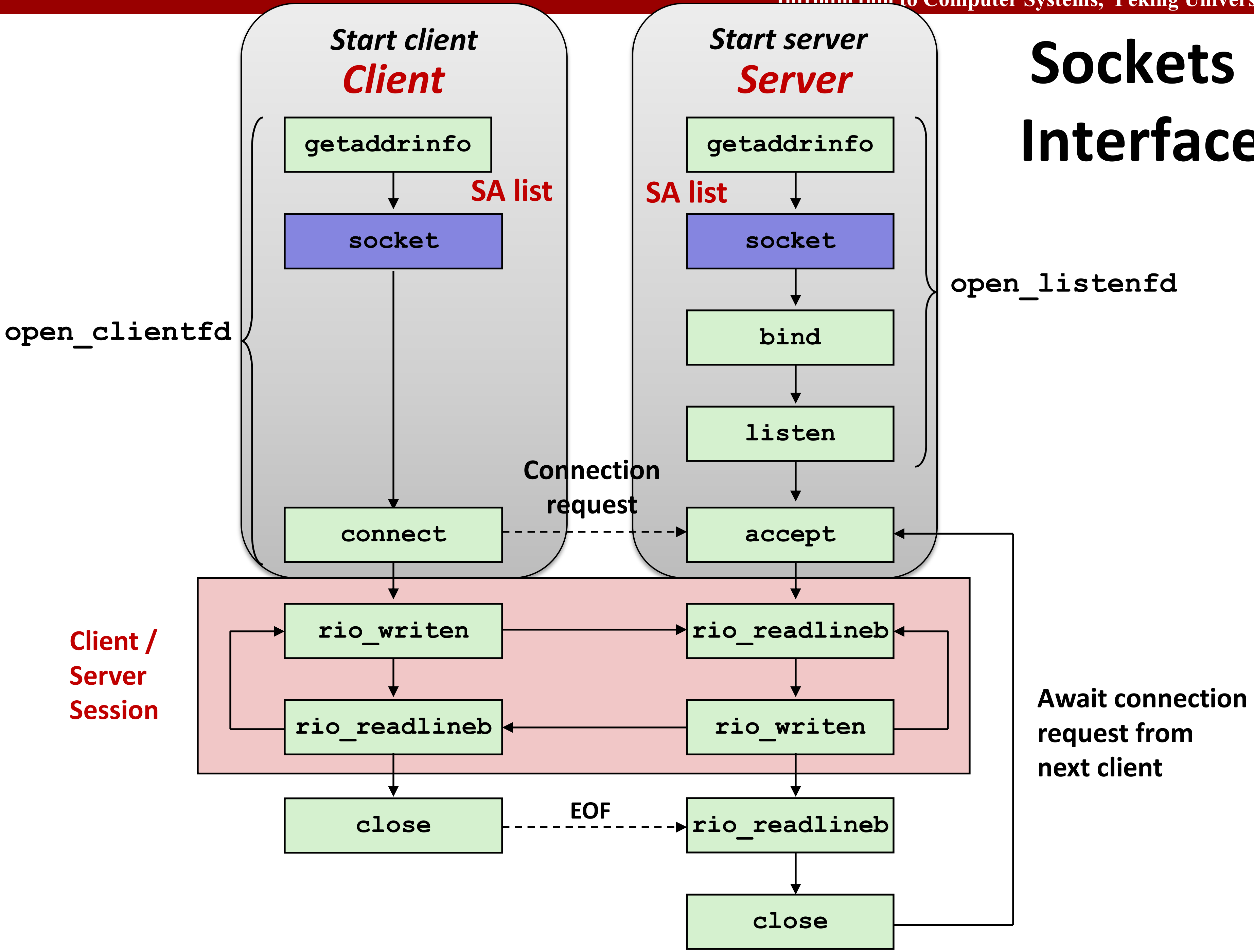


Review: getaddrinfo

- **getaddrinfo** converts string representations of hostnames, host addresses, ports, service names to socket address structures



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);
```

Protocol specific!

Indicates that we are using 32-bit IPV4 addresses

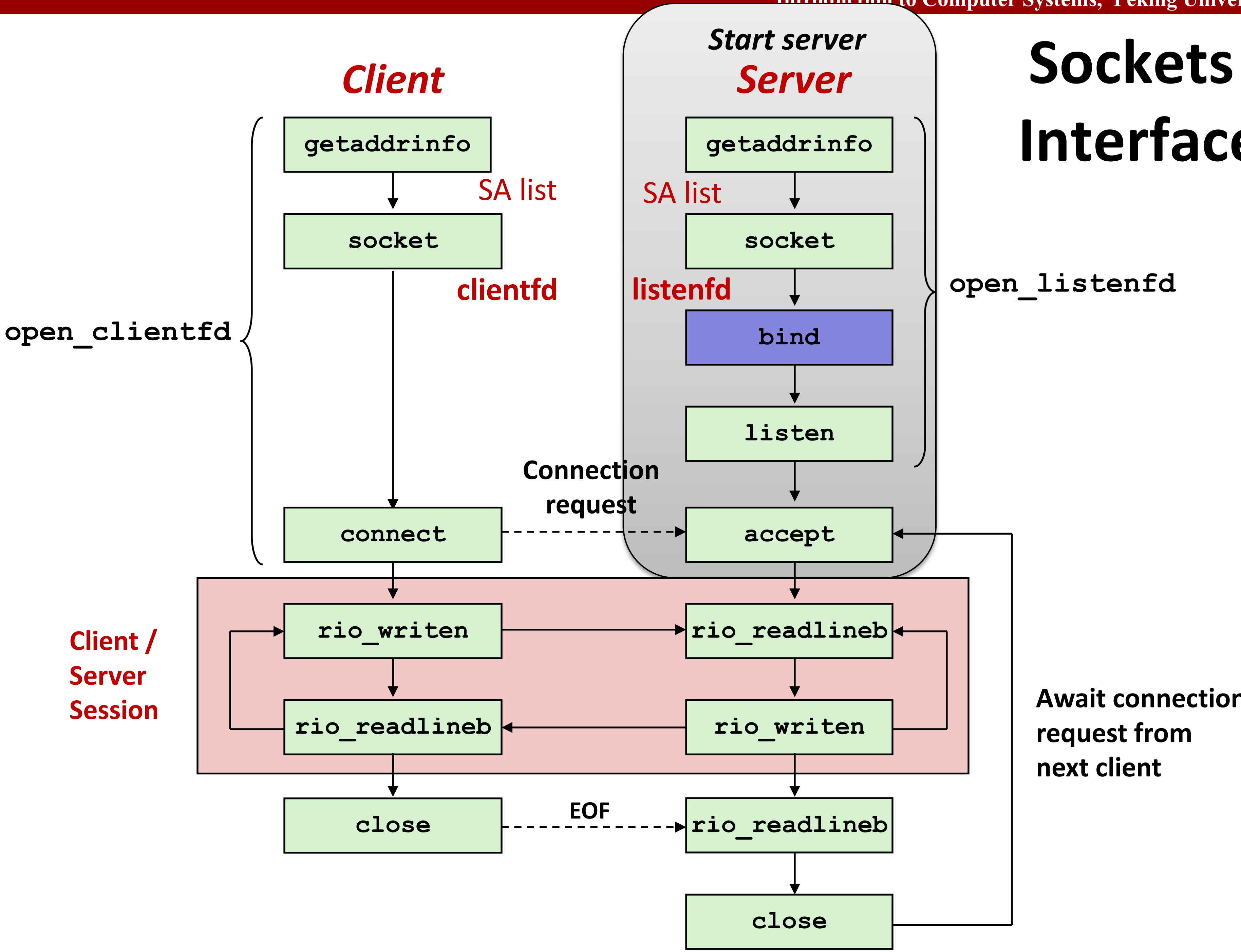
Indicates that the socket will be the end point of a reliable (TCP) connection

- Example:

```
int clientfd = socket(ai->ai_family, ai->ai_socktype,
                      ai->ai_protocol);
```

Use getaddrinfo to generate the parameters automatically, so that code is protocol independent.

Sockets Interface



Sockets Interface: `bind`

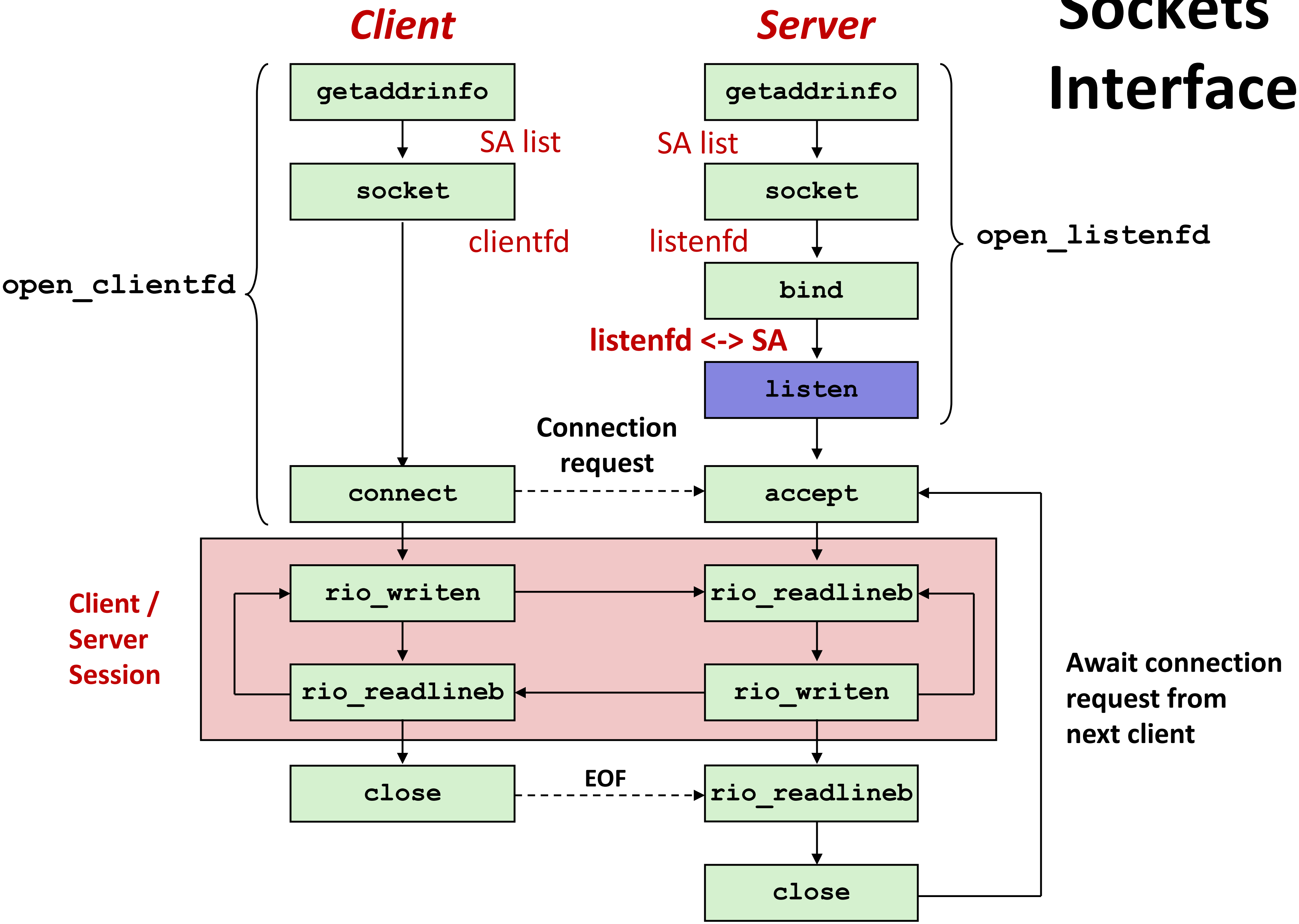
- A server uses `bind` to ask the kernel to associate the server's socket address with a socket descriptor:

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

Our convention: `typedef struct sockaddr SA;`

- 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`

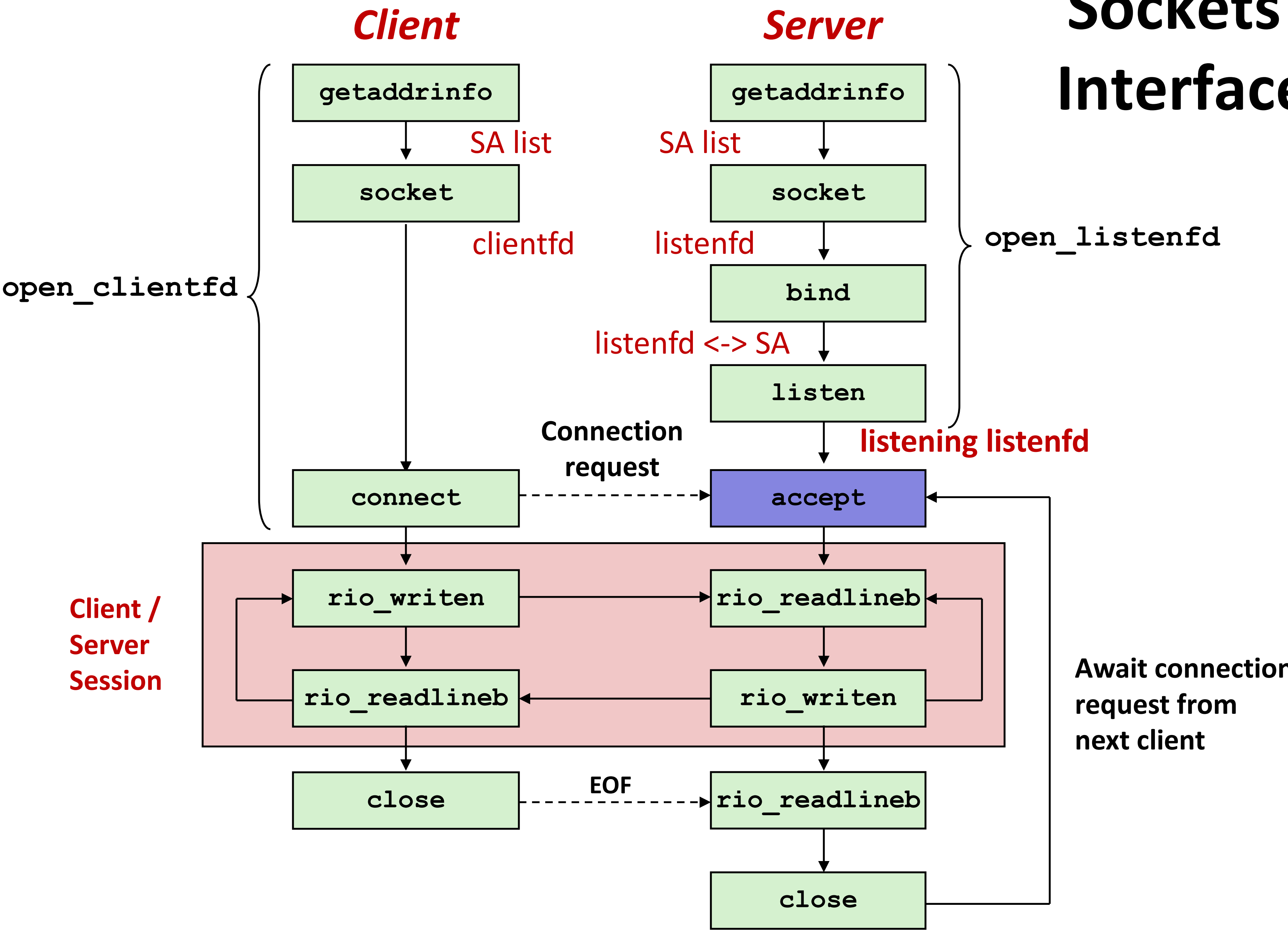
- Kernel assumes that descriptor from socket function is an *active socket* that will be on the client end
- A server calls the listen function to tell the kernel that a descriptor will be used by a server rather than a client:

```
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 (128-ish by default)

Sockets Interface



Sockets Interface: `accept`

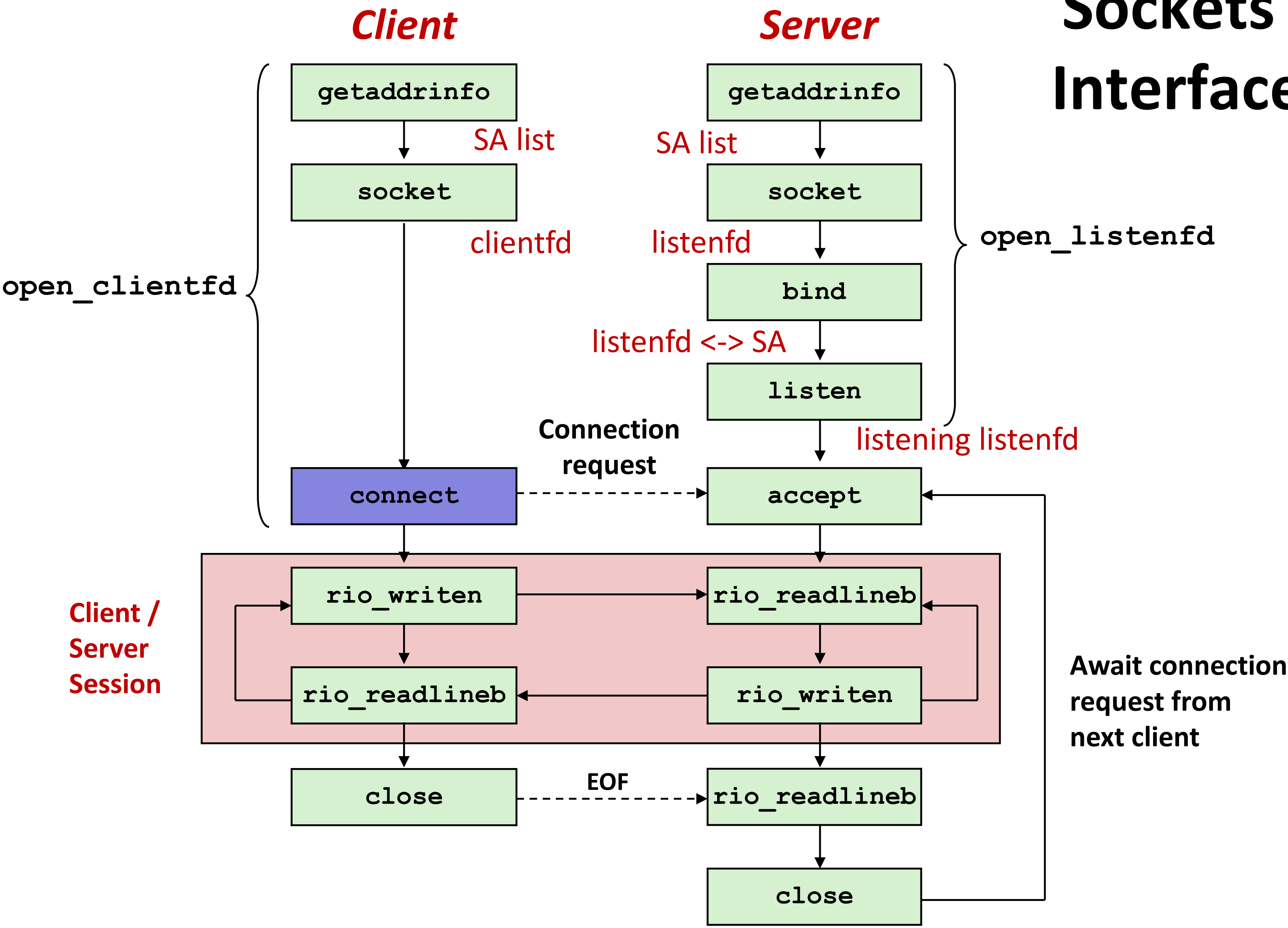
- Servers wait for connection requests from clients by calling `accept`:

```
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* `connfd` 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);
```

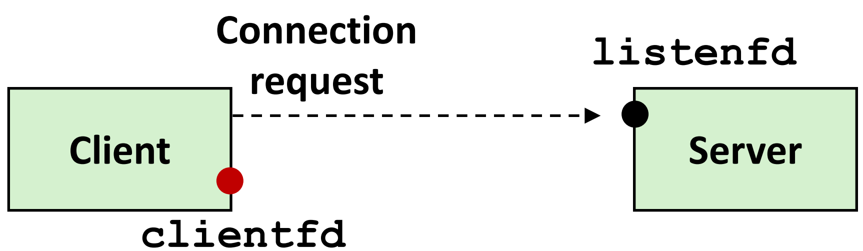
- **Attempts to establish a connection with server at socket address `addr`**
  - If successful, then **`clientfd`** is now ready for reading and writing.
  - Resulting connection is characterized by socket pair

    (**`x:y, addr.sin_addr:addr.sin_port`**)
    - **`x`** is client address
    - **`y`** is ephemeral port that uniquely identifies client process on client host

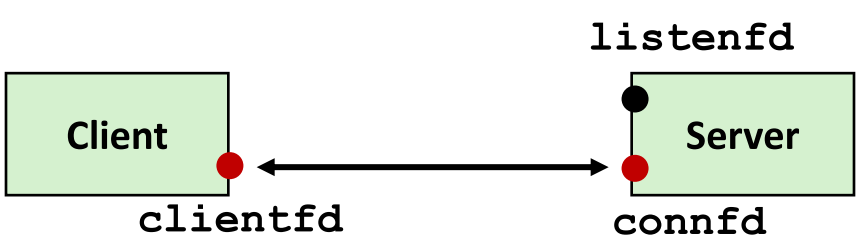
Best practice is to use `getaddrinfo` to supply the arguments `addr` and `addrlen`.

`connect`/`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`

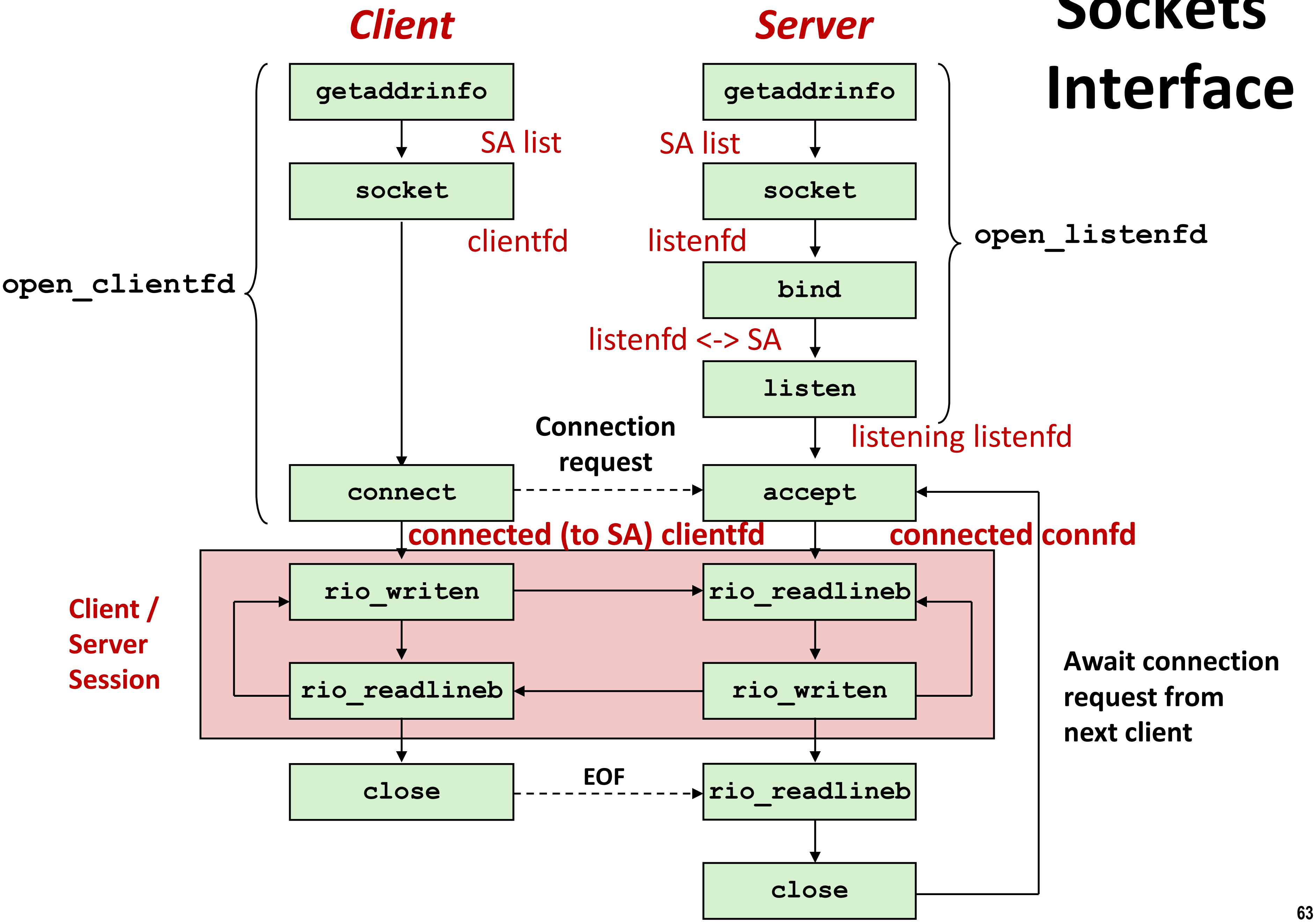
Connected vs. Listening Descriptors

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

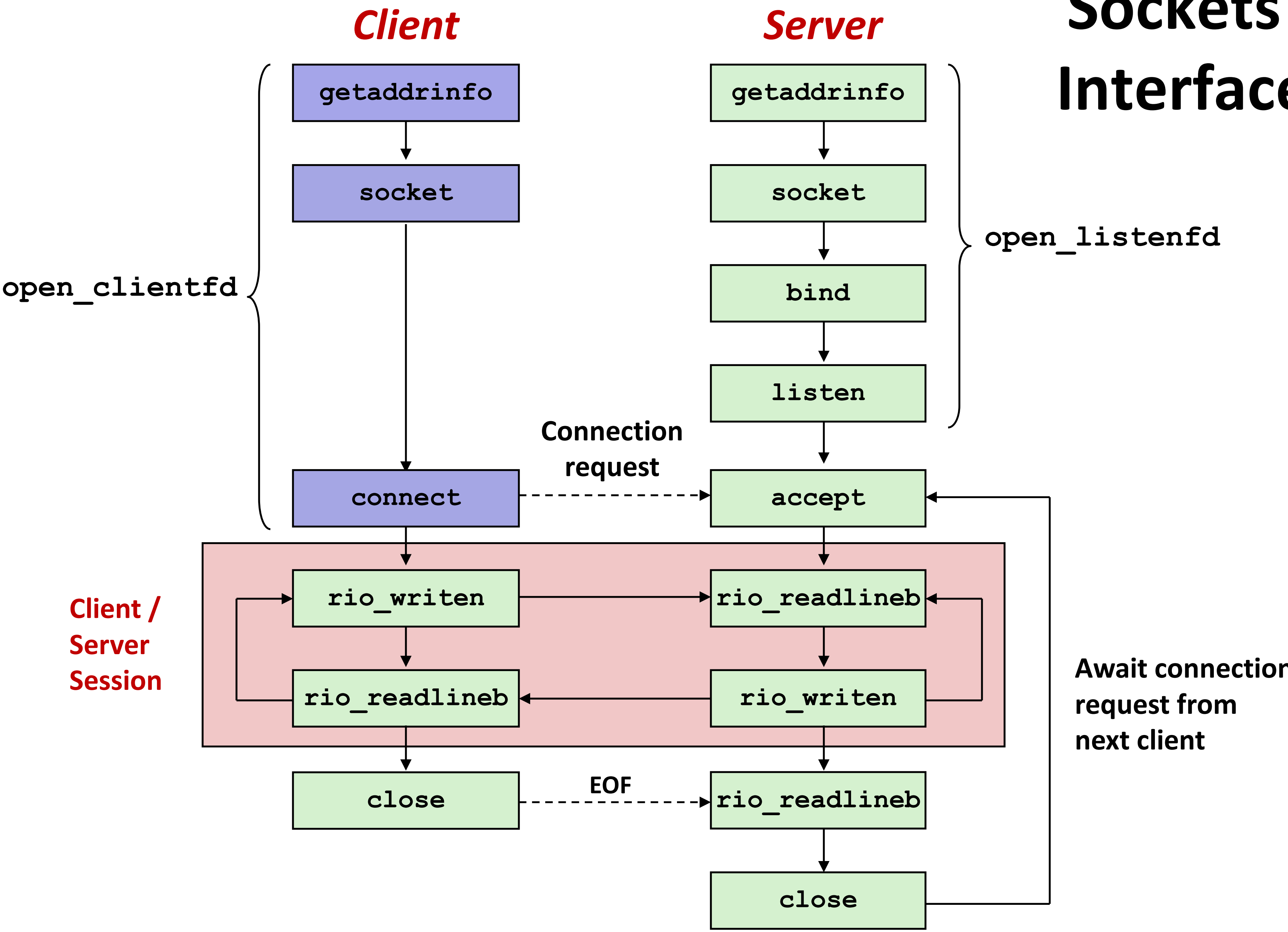
- **Connected descriptor**
  - End point of the connection between client and server
  - A new descriptor is created each time the server accepts a connection request from a client
  - Exists only as long as it takes to service client

- **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



Sockets Interface



Sockets Helper: open_clientfd

- Establish a connection with a server

```
int open_clientfd(char *hostname, char *port) {
  int clientfd;
  struct addrinfo hints, *listp, *p;

  /* Get a list of potential server addresses */
  memset(&hints, 0, sizeof(struct addrinfo));
  hints.ai_socktype = SOCK_STREAM;  /* Open a connection */
  hints.ai_flags = AI_NUMERICSERV;  /* …using numeric port arg. */
  hints.ai_flags |= AI_ADDRCONFIG;  /* Recommended for connections */
  Getaddrinfo(hostname, port, &hints, &listp);
```

csapp.c

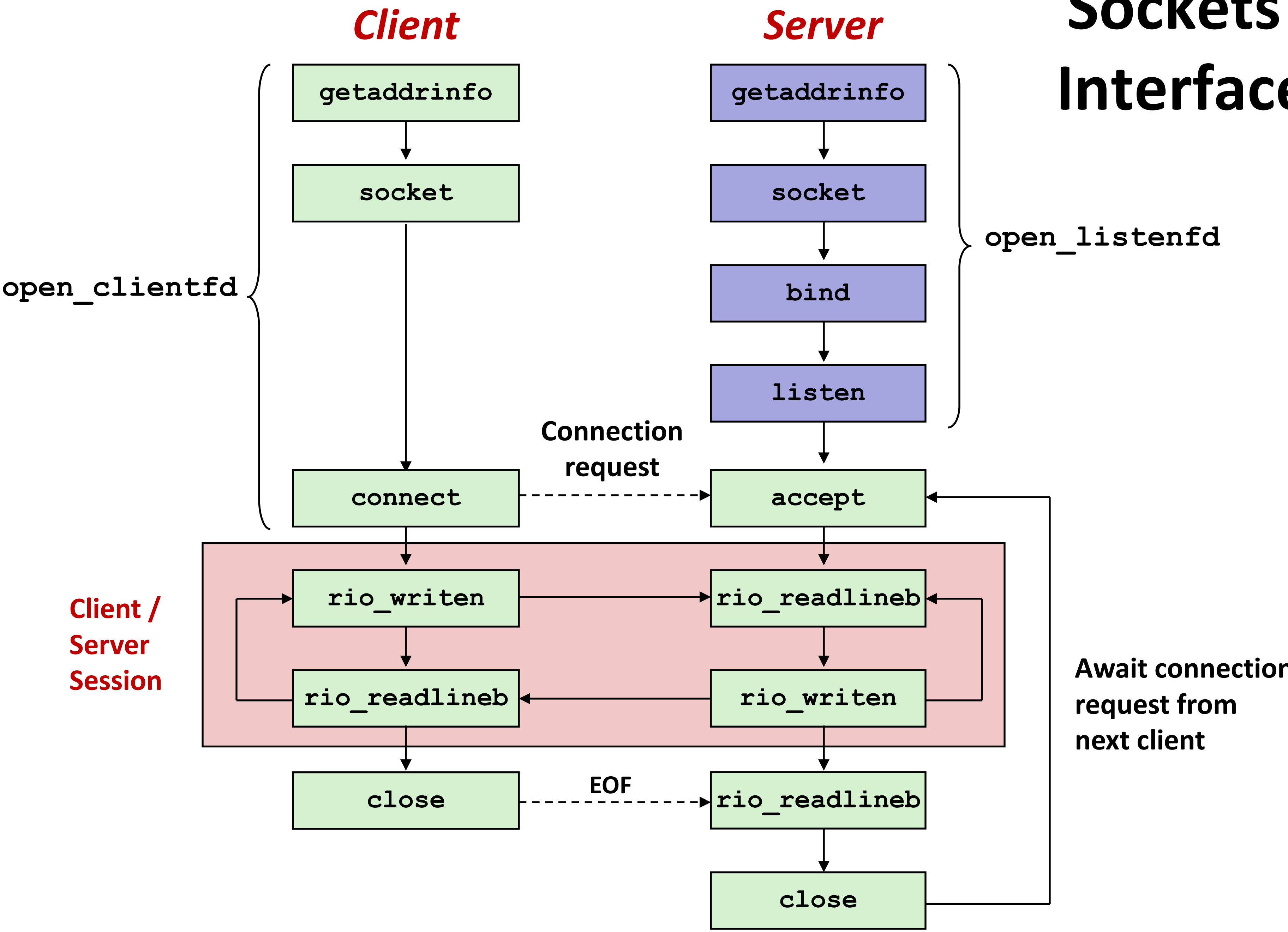
AI_ADDRCONFIG means "use whichever of IPv4 and IPv6 works on this computer". Good practice for clients, not for servers.

Sockets Helper: `open_clientfd` (cont)

```
    /* Walk the list for one that we can successfully connect to */
    for (p = listp; p; p = p->ai_next) {
        /* Create a socket descriptor */
        if ((clientfd = socket(p->ai_family, p->ai_socktype,
                               p->ai_protocol)) < 0)
            continue; /* Socket failed, try the next */

        /* Connect to the server */
        if (connect(clientfd, p->ai_addr, p->ai_addrlen) != -1)
            break; /* Success */
        Close(clientfd); /* Connect failed, try another */
    }

    /* Clean up */
    Freeaddrinfo(listp);
    if (!p) /* All connects failed */
        return -1;
    else    /* The last connect succeeded */
        return clientfd;
}
```

csapp.c

Sockets Interface



Sockets Helper: `open_listenfd`

- Create a listening descriptor that can be used to accept connection requests from clients.

```
int open_listenfd(char *port)
{
    struct addrinfo hints, *listp, *p;
    int listenfd, optval=1;

    /* Get a list of potential server addresses */
    memset(&hints, 0, sizeof(struct addrinfo));
    hints.ai_socktype = SOCK_STREAM;              /* Accept connect. */
    hints.ai_flags = AI_PASSIVE | AI_ADDRCONFIG; /* …on any IP addr */
    hints.ai_flags |= AI_NUMERICSERV;            /* …using port no. */
    Getaddrinfo(NULL, port, &hints, &listp);
```

csapp.c

`AI_PASSIVE` means "I plan to listen on this socket."

`AI_ADDRCONFIG` normally not used for servers, but we use it for convenience

Sockets Helper: open_listenfd (cont)

```
    /* Walk the list for one that we can bind to */
    for (p = listp; p; p = p->ai_next) {
        /* Create a socket descriptor */
        if ((listenfd = socket(p->ai_family, p->ai_socktype,
                               p->ai_protocol)) < 0)
            continue;  /* Socket failed, try the next */

        /* Eliminates "Address already in use" error from bind */
        Setsockopt(listenfd, SOL_SOCKET, SO_REUSEADDR,
                   (const void *)&optval , sizeof(int));

        /* Bind the descriptor to the address */
        if (bind(listenfd, p->ai_addr, p->ai_addrlen) == 0)
            break; /* Success */
        Close(listenfd); /* Bind failed, try the next */
    }
```

csapp.c

A production server would not break out of the loop on the first success.
We do that for simplicity only.

Sockets Helper: open_listenfd (cont)

```
    /* Clean up */
    Freeaddrinfo(listp);
    if (!p) /* No address worked */
        return -1;

    /* Make it a listening socket ready to accept conn. requests */
    if (listen(listenfd, LISTENQ) < 0) {
        Close(listenfd);
        return -1;
    }
    return listenfd;
}
```

csapp.c

- **Key point:** open_clientfd and open_listenfd are both independent of any particular version of IP.

Testing Servers Using `telnet`

- **The `telnet` program is invaluable for testing servers that transmit ASCII strings over Internet connections**
  - Our simple echo server
  - Web servers
  - Mail servers

- **Usage:**
  - ***`linux> telnet <host> <portnumber>`***
  - Creates a connection with a server running on ***`<host>`*** and listening on port ***`<portnumber>`***

Testing the Echo Server With `telnet`

```
whaleshark> ./echoserveri 15213
Connected to (MAKOSHARK.ICS.CS.CMU.EDU, 50280)
server received 11 bytes
server received 8 bytes



makoshark> telnet whaleshark.ics.cs.cmu.edu 15213
Trying 128.2.210.175...
Connected to whaleshark.ics.cs.cmu.edu (128.2.210.175).
Escape character is '^]'.
Hi there!
Hi there!
Howdy!
Howdy!
^]
telnet> quit
Connection closed.
makoshark>
```

For More Information

- **W. Richard Stevens et. al. "Unix Network Programming: The Sockets Networking API", Volume 1, Third Edition, Prentice Hall, 2003**
  - THE network programming bible.
- **Michael Kerrisk, "The Linux Programming Interface", No Starch Press, 2010**
  - THE Linux programming bible.
- **Complete versions of all code in this lecture is available from the 213 schedule page.**
  - `http://www.cs.cmu.edu/~213/schedule.html`
  - csapp.{.c,h}, hostinfo.c, echoclient.c, echoserveri.c, tiny.c, adder.c
  - You can use any of this code in your assignments.

Additional slides

Key Layers of the Internet

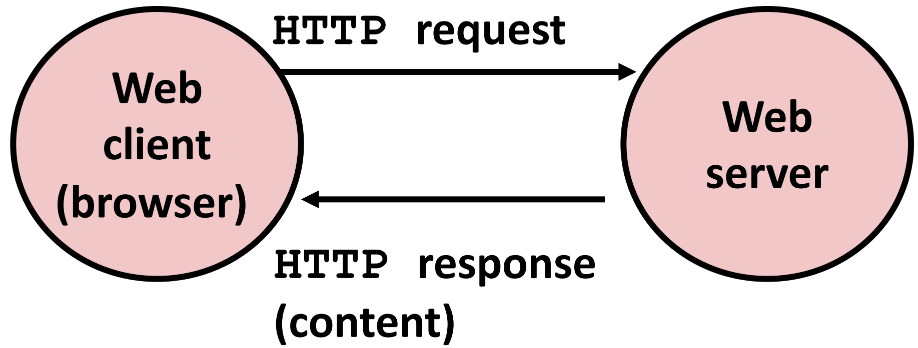
Key Layers of the Internet

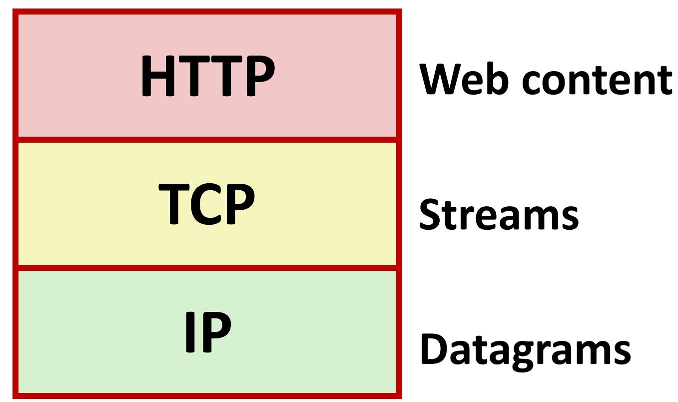
early milestones	Key Layers of the Internet	milestones
email@-1971 Ray Tomlinson	CONTENT	1987-HyperCard Bill Atkinson
Archie-1990 Emtage & Deutsch	SEARCH ENGINE*	1998-Google Brin & Page
DOS Houdini-1986 Neil Larson	BROWSERS	1993-Mosaic Marc Andreessen
(Vannevar Bush, Ted Nelson, Douglas Engelbart)	WORLD WIDE WEB	1990-http:// Tim Berners-Lee
ARPANET-1969 J.C.R. Licklider	INTERNET	1975-TCP/IP Cerf & Kahn
SAGE-1956 George Valley	NETWORKS	1973-Ethernet Robert Metcalfe
Z3-1941 Konrad Zuse	COMPUTERS	1976-Apple Jobs & Wozniak

https://en.wikipedia.org/wiki/World_Wide_Web

Web Server Basics

- **Clients and servers communicate using the HyperText Transfer Protocol (HTTP)**
  - Client and server establish TCP connection
  - Client requests content
  - Server responds with requested content
  - Client and server close connection (eventually)
- **Current version is HTTP/1.1**
  - RFC 2616, June, 1999.





`http://www.w3.org/Protocols/rfc2616/rfc2616.html`

Web Content

- **Web servers return *content* to clients**
  - *content:* a sequence of bytes with an associated MIME (Multipurpose Internet Mail Extensions) type

- **Example MIME types**
  - **`text/html`** HTML document
  - **`text/plain`** Unformatted text
  - **`image/gif`** Binary image encoded in GIF format
  - **`image/png`** Binary image encoded in PNG format
  - **`image/jpeg`** Binary image encoded in JPEG format

You can find the complete list of MIME types at:
`http://www.iana.org/assignments/media-types/media-types.xhtml`

Static and Dynamic Content

- **The content returned in HTTP responses can be either *static* or *dynamic***
  - *Static content*: content stored in files and retrieved in response to an HTTP request
    - Examples: HTML files, images, audio clips, Javascript programs
    - Request identifies which content file
  - *Dynamic content*: content produced on-the-fly in response to an HTTP request
    - Example: content produced by a program executed by the server on behalf of the client
    - Request identifies file containing executable code
- ***Web content associated with a file that is managed by the server***

URLs and how clients and servers use them

- **Unique name for a file: URL (Universal Resource Locator)**
- **Example URL: `http://www.cmu.edu:80/index.html`**
- **Clients use *prefix* (`http://www.cmu.edu:80`) to infer:**
  - What kind (protocol) of server to contact (HTTP)
  - Where the server is (**`www.cmu.edu`**)
  - What port it is listening on (80)
- **Servers use *suffix* (`/index.html`) to:**
  - Determine if request is for static or dynamic content.
    - No hard and fast rules for this
    - One convention: executables reside in **`cgi-bin`** directory
  - Find file on file system
    - Initial "/" in suffix denotes home directory for requested content.
    - Minimal suffix is "/", which server expands to configured default filename (usually, **`index.html`**)

HTTP Requests

- **HTTP request is a *request line*, followed by zero or more *request headers***
- **Request line: `<method> <uri> <version>`**
  - `<method>` is one of **`GET`**, **`POST`**, **`OPTIONS`**, **`HEAD`**, **`PUT`**, **`DELETE`**, or **`TRACE`**
  - `<uri>` is typically URL for proxies, URL suffix for servers
    - A URL is a type of URI (Uniform Resource Identifier)
    - See http://www.ietf.org/rfc/rfc2396.txt
  - `<version>` is HTTP version of request (**`HTTP/1.0`** or **`HTTP/1.1`**)
- **Request headers: `<header name>: <header data>`**
  - Provide additional information to the server

HTTP Responses

- HTTP response is a *response line* followed by zero or more *response headers*, possibly followed by *content*, with blank line ("`\r\n`") separating headers from content.

- Response line:

  `<version> <status code> <status msg>`

  - <version> is HTTP version of the response
  - <status code> is numeric status
  - <status msg> is corresponding English text
    - `200 OK` Request was handled without error
    - `301 Moved` Provide alternate URL
    - `404 Not found` Server couldn't find the file

- Response headers: `<header name>: <header data>`
  - Provide additional information about response
  - `Content-Type:` MIME type of content in response body
  - `Content-Length:` Length of content in response body

Example HTTP Transaction

```
whaleshark> telnet www.cmu.edu 80           Client: open connection to server
Trying 128.2.42.52...                       Telnet prints 3 lines to terminal
Connected to WWW-CMU-PROD-VIP.ANDREW.cmu.edu.
Escape character is '^]'.
GET / HTTP/1.1                              Client: request line
Host: www.cmu.edu                           Client: required HTTP/1.1 header
                                            Client: blank line terminates headers
HTTP/1.1 301 Moved Permanently              Server: response line
Date: Wed, 05 Nov 2014 17:05:11 GMT         Server: followed by 5 response headers
Server: Apache/1.3.42 (Unix)                Server: this is an Apache server
Location: http://www.cmu.edu/index.shtml    Server: page has moved here
Transfer-Encoding: chunked                  Server: response body will be chunked
Content-Type: text/html; charset=...        Server: expect HTML in response body
                                            Server: empty line terminates headers
15c                                         Server: first line in response body
<HTML><HEAD>                                Server: start of HTML content
…
</BODY></HTML>                              Server: end of HTML content
0                                           Server: last line in response body
Connection closed by foreign host.          Server: closes connection
```

- HTTP standard requires that each text line end with "`\r\n`"
- Blank line ("`\r\n`") terminates request and response headers

Example HTTP Transaction, Take 2

```
whaleshark> telnet www.cmu.edu 80          Client: open connection to server
Trying 128.2.42.52...                      Telnet prints 3 lines to terminal
Connected to WWW-CMU-PROD-VIP.ANDREW.cmu.edu.
Escape character is '^]'.
GET /index.shtml HTTP/1.1                  Client: request line
Host: www.cmu.edu                          Client: required HTTP/1.1 header
                                           Client: blank line terminates headers
HTTP/1.1 200 OK                            Server: response line
Date: Wed, 05 Nov 2014 17:37:26 GMT        Server: followed by 4 response headers
Server: Apache/1.3.42 (Unix)
Transfer-Encoding: chunked
Content-Type: text/html; charset=...
                                           Server: empty line terminates headers
1000                                       Server: begin response body
<html ..>                                  Server: first line of HTML content
…
</html>
0                                          Server: end response body
Connection closed by foreign host.         Server: close connection
```

Example HTTP(S) Transaction, Take 3

```
whaleshark> openssl s_client www.cs.cmu.edu:443
CONNECTED(00000005)
…
Certificate chain
…
-
Server certificate
-----BEGIN CERTIFICATE-----
MIIGDjCCBPagAwIBAgIRAMiF7LBPDoySilnNoU+mp+gwDQYJKoZIhvcNAQELBQAw
djELMAkGA1UEBhMCVVMxCzAJBgNVBAgTAk1JMRIwEAYDVQQHEwlBbm4gQXJib3Ix
EjAQBgNVBAoTCUludGVybmV0MjERMA8GA1UECxMISW5Db21tb24xHzAdBgNVBAMT
wkWkvDVBBCwKXrShVxQNsj6J
…
-----END CERTIFICATE-----
subject=/C=US/postalCode=15213/ST=PA/L=Pittsburgh/street=5000 Forbes
Ave/O=Carnegie Mellon University/OU=School of Computer
Science/CN=www.cs.cmu.edu         issuer=/C=US/ST=MI/L=Ann
Arbor/O=Internet2/OU=InCommon/CN=InCommon RSA Server CA
SSL handshake has read 6274 bytes and written 483 bytes
…
>GET / HTTP/1.0

HTTP/1.1 200 OK
Date: Tue, 12 Nov 2019 04:22:15 GMT
Server: Apache/2.4.10 (Ubuntu)
Set-Cookie: SHIBLOCATION=scsweb; path=/; domain=.cs.cmu.edu
... HTML Content Continues Below ...
```

Tiny Web Server

- **Tiny Web server described in text**
  - Tiny is a sequential Web server
  - Serves static and dynamic content to real browsers
    - text files, HTML files, GIF, PNG, and JPEG images
  - 239 lines of commented C code
  - Not as complete or robust as a real Web server
    - You can break it with poorly-formed HTTP requests (e.g., terminate lines with "`\n`" instead of "`\r\n`")

Tiny Operation

- **Accept connection from client**
- **Read request from client (via connected socket)**
- **Split into <method> <uri> <version>**
  - If method not GET, then return error
- **If URI contains "`cgi-bin`" then serve dynamic content**
  - (Would do wrong thing if had file "`abcgi-bingo.html`")
  - Fork process to execute program
- **Otherwise serve static content**
  - Copy file to output

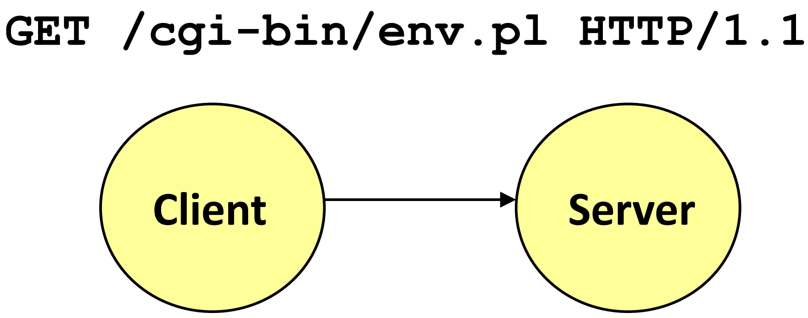
Tiny Serving Static Content

```
void serve_static(int fd, char *filename, int filesize)
{
    int srcfd;
    char *srcp, filetype[MAXLINE], buf[MAXBUF];

    /* Send response headers to client */
    get_filetype(filename, filetype);
    sprintf(buf, "HTTP/1.0 200 OK\r\n");
    sprintf(buf, "%sServer: Tiny Web Server\r\n", buf);
    sprintf(buf, "%sConnection: close\r\n", buf);
    sprintf(buf, "%sContent-length: %d\r\n", buf, filesize);
    sprintf(buf, "%sContent-type: %s\r\n\r\n", buf, filetype);
    Rio_writen(fd, buf, strlen(buf));

    /* Send response body to client */
    srcfd = Open(filename, O_RDONLY, 0);
    srcp = Mmap(0, filesize, PROT_READ, MAP_PRIVATE, srcfd, 0);
    Close(srcfd);
    Rio_writen(fd, srcp, filesize);
    Munmap(srcp, filesize);
}
```

tiny.c

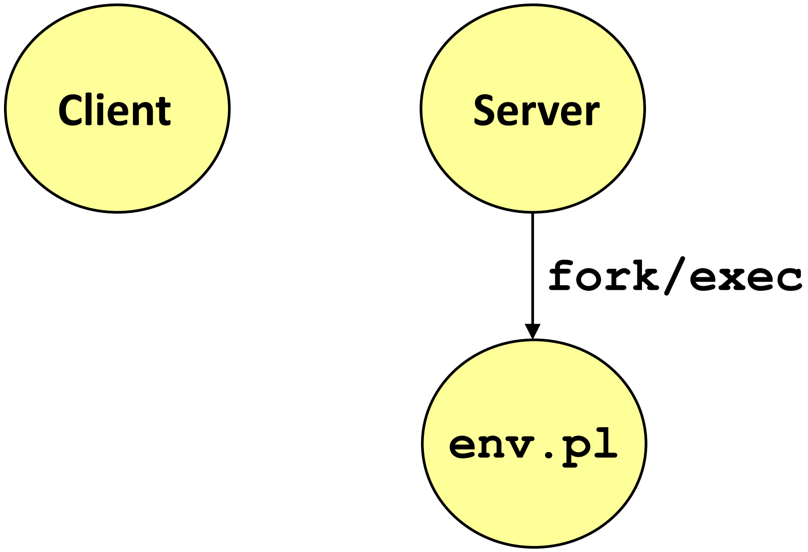
Serving Dynamic Content

- Client sends request to server
- If request URI contains the string "`/cgi-bin`", the Tiny server assumes that the request is for dynamic content



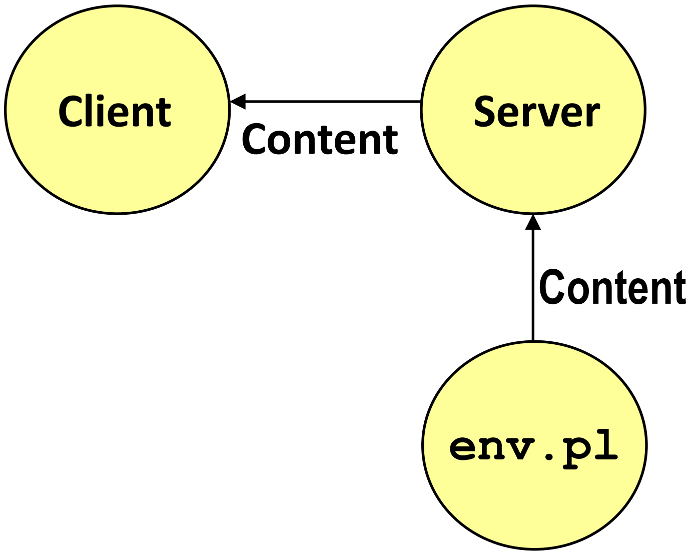
Serving Dynamic Content (cont)

- The server creates a child process and runs the program identified by the URI in that process



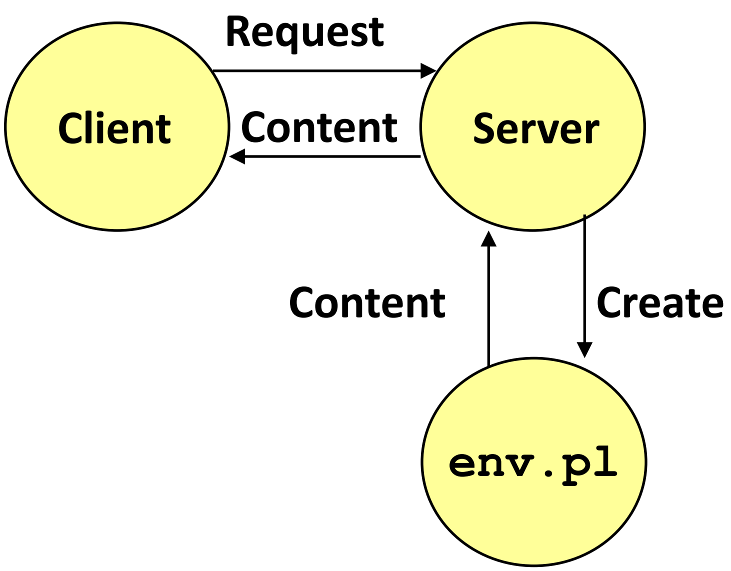
Serving Dynamic Content (cont)

- The child runs and generates the dynamic content
- The server captures the content of the child and forwards it without modification to the client



Issues in Serving Dynamic Content

- How does the client pass program arguments to the server?
- How does the server pass these arguments to the child?
- How does the server pass other info relevant to the request to the child?
- How does the server capture the content produced by the child?
- These issues are addressed by the **Common Gateway Interface (CGI)** specification.



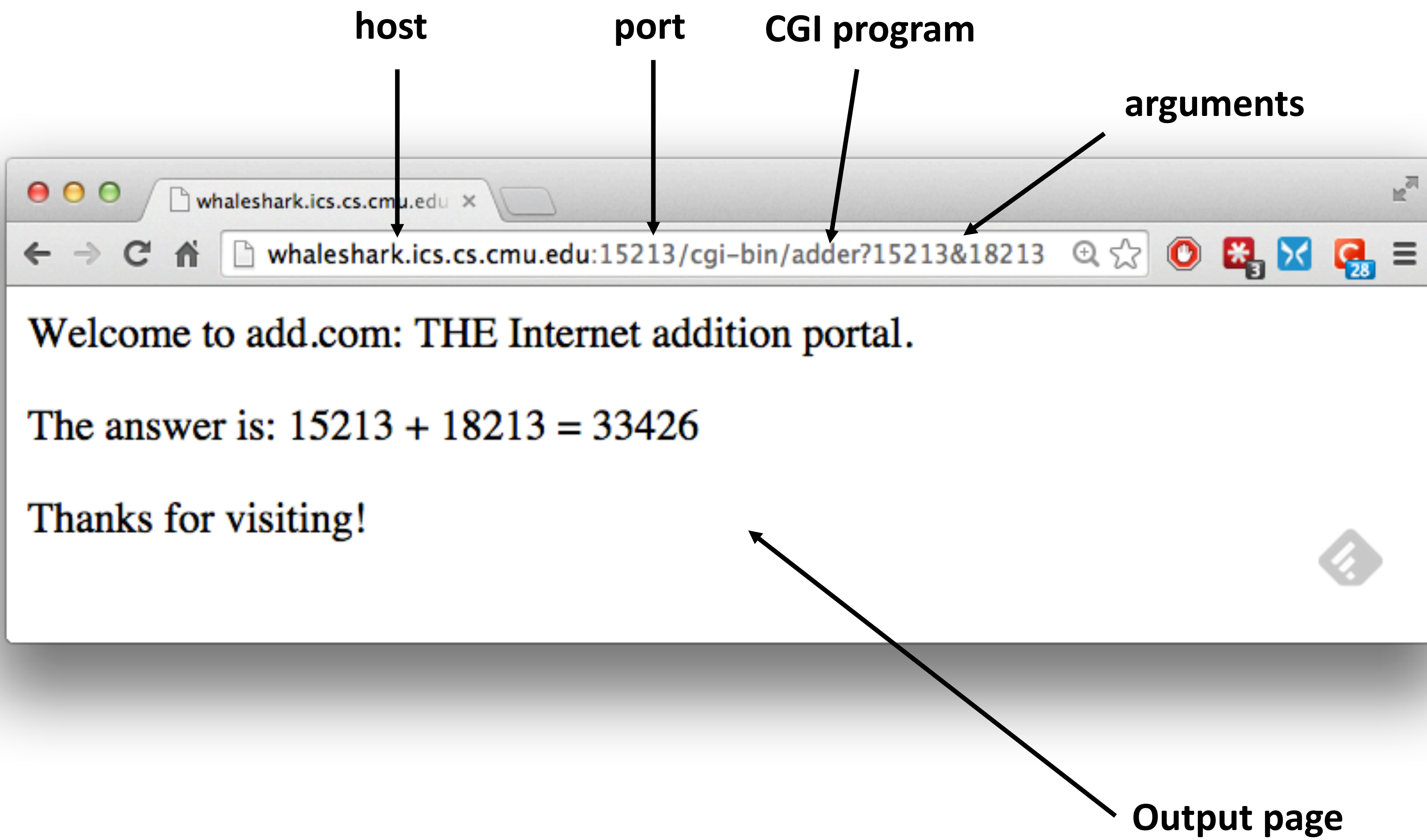
CGI

- **Because the children are written according to the CGI spec, they are often called *CGI programs.***

- **However, CGI really defines a simple standard for transferring information between the client (browser), the server, and the child process.**

- **CGI is the original standard for generating dynamic content. Has been largely replaced by other, faster techniques:**
  - E.g., fastCGI, Apache modules, Java servlets, Rails controllers
  - Avoid having to create process on the fly (expensive and slow).

The add.com Experience



Serving Dynamic Content With GET

- <u>Question:</u> How does the client pass arguments to the server?
- <u>Answer:</u> The arguments are appended to the URI

- Can be encoded directly in a URL typed to a browser or a URL in an HTML link
  - `http://add.com/cgi-bin/adder?15213&18213`
  - **`adder`** is the CGI program on the server that will do the addition.
  - argument list starts with "**`?`**"
  - arguments separated by "**`&`**"
  - spaces represented by "**`+`**" `or` "**`%20`**"

Serving Dynamic Content With GET

- URL suffix:
  - `cgi-bin/adder?15213&18213`

- Result displayed on browser:

```
Welcome to add.com: THE Internet
addition portal.

The answer is: 15213 + 18213 = 33426

Thanks for visiting!
```

Serving Dynamic Content With GET

- **Question: How does the server pass these arguments to the child?**
- **Answer: In environment variable QUERY_STRING**
  - A single string containing everything after the "**?**"
  - For add: **QUERY_STRING** = "**15213&18213**"

```
/* Extract the two arguments */
if ((buf = getenv("QUERY_STRING")) != NULL) {
    p = strchr(buf, '&');
    *p = '\0';
    strcpy(arg1, buf);
    strcpy(arg2, p+1);
    n1 = atoi(arg1);
    n2 = atoi(arg2);
}
```

adder.c

Serving Dynamic Content with GET

- **Question:** How does the server capture the content produced by the child?
- **Answer:** The child generates its output on `stdout`. Server uses dup2 to redirect `stdout` to its connected socket.

```
void serve_dynamic(int fd, char *filename, char *cgiargs)
{
    char buf[MAXLINE], *emptylist[] = { NULL };

    /* Return first part of HTTP response */
    sprintf(buf, "HTTP/1.0 200 OK\r\n");
    Rio_writen(fd, buf, strlen(buf));
    sprintf(buf, "Server: Tiny Web Server\r\n");
    Rio_writen(fd, buf, strlen(buf));

    if (Fork() == 0) { /* Child */
        /* Real server would set all CGI vars here */
        setenv("QUERY_STRING", cgiargs, 1);
        Dup2(fd, STDOUT_FILENO);         /* Redirect stdout to client */
        Execve(filename, emptylist, environ); /* Run CGI program */
    }
    Wait(NULL); /* Parent waits for and reaps child */
}
```

tiny.c

Serving Dynamic Content with GET

- Notice that only the CGI child process knows the content type and length, so it must generate those headers.

```
/* Make the response body */
sprintf(content, "Welcome to add.com: ");
sprintf(content, "%sTHE Internet addition portal.\r\n<p>", content);
sprintf(content, "%sThe answer is: %d + %d = %d\r\n<p>",
        content, n1, n2, n1 + n2);
sprintf(content, "%sThanks for visiting!\r\n", content);

/* Generate the HTTP response */
printf("Content-length: %d\r\n", (int)strlen(content));
printf("Content-type: text/html\r\n\r\n");
printf("%s", content);
fflush(stdout);

exit(0);
```

adder.c

Serving Dynamic Content With GET

```
bash:makoshark> telnet whaleshark.ics.cs.cmu.edu 15213
Trying 128.2.210.175...
Connected to whaleshark.ics.cs.cmu.edu (128.2.210.175).
Escape character is '^]'.
GET /cgi-bin/adder?15213&18213 HTTP/1.0

HTTP/1.0 200 OK
Server: Tiny Web Server
Connection: close
Content-length: 117
Content-type: text/html

Welcome to add.com: THE Internet addition portal.
<p>The answer is: 15213 + 18213 = 33426
<p>Thanks for visiting!
Connection closed by foreign host.
bash:makoshark>
```

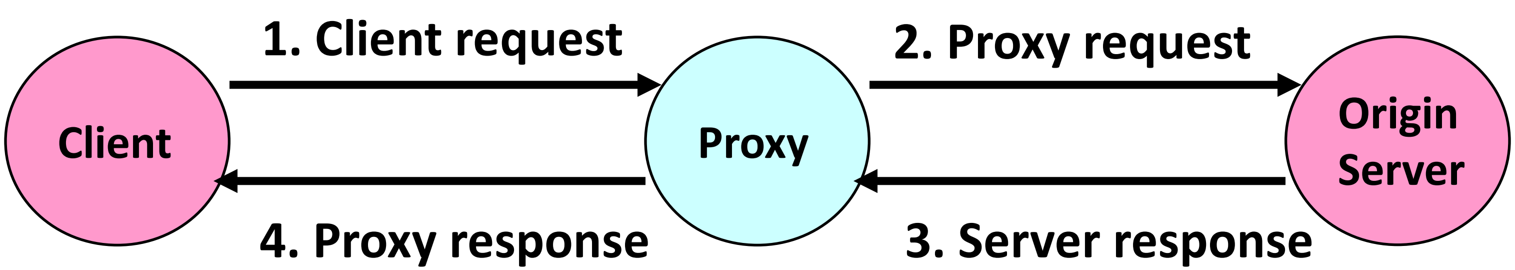
HTTP request sent by client

HTTP response generated by the server

HTTP response generated by the CGI program

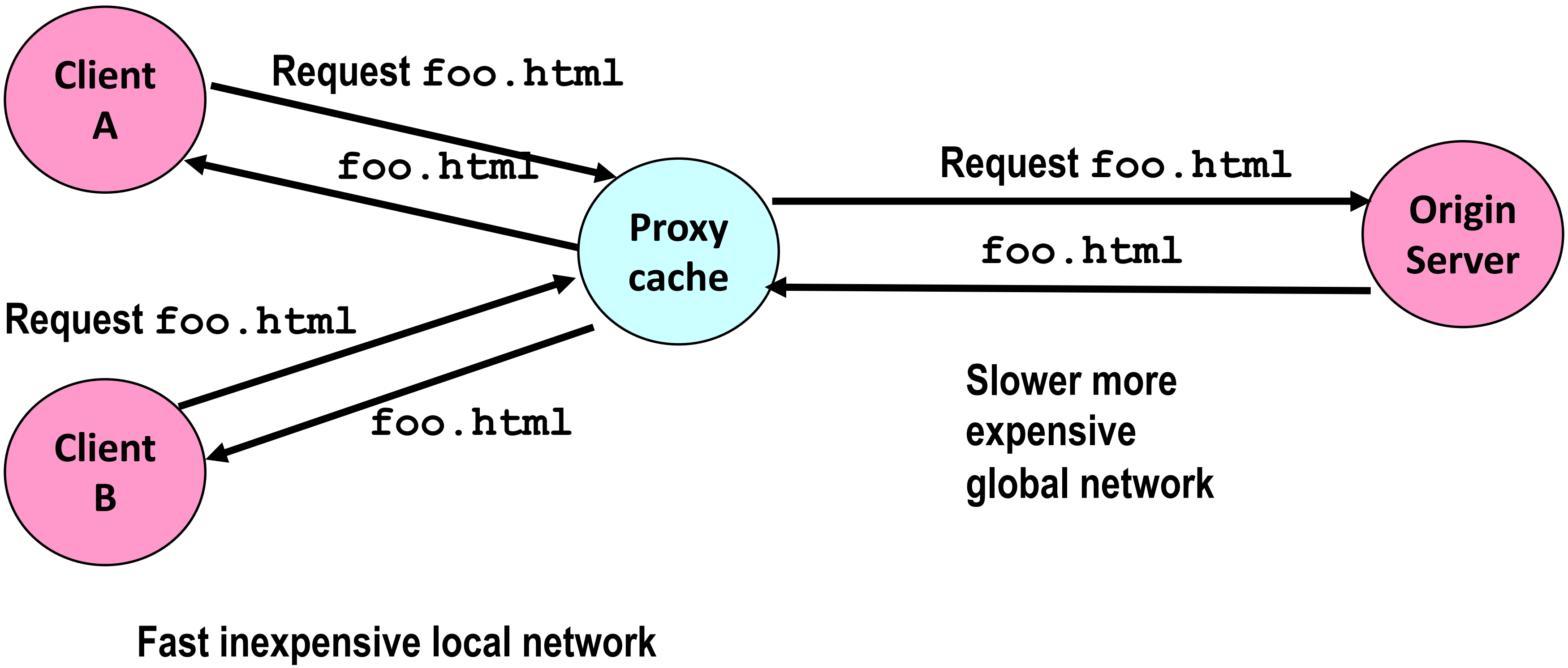
Proxies

- **A *proxy* is an intermediary between a client and an *origin server***
  - To the client, the proxy acts like a server
  - To the server, the proxy acts like a client



Why Proxies?

- **Can perform useful functions as requests and responses pass by**
  - Examples: Caching, logging, anonymization, filtering, transcoding



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

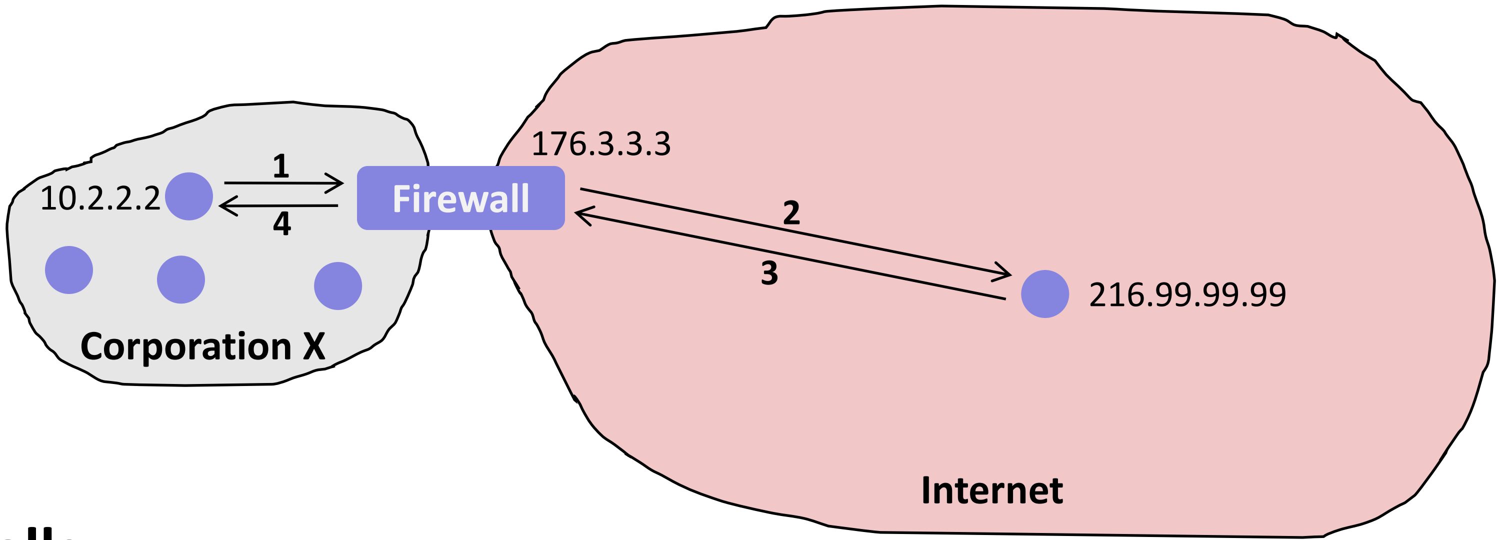
- **Shortcomings**
  - There aren't enough IP addresses available
  - Don't want everyone to have access or knowledge of all other hosts
  - Security issues mandate secrecy & authentication

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