Network Programming: Part I

Sockets Interface

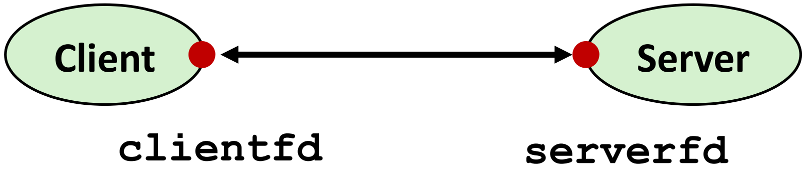
- **Set of system-level functions used in conjunction with Unix I/O to build network applications.**

- **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**

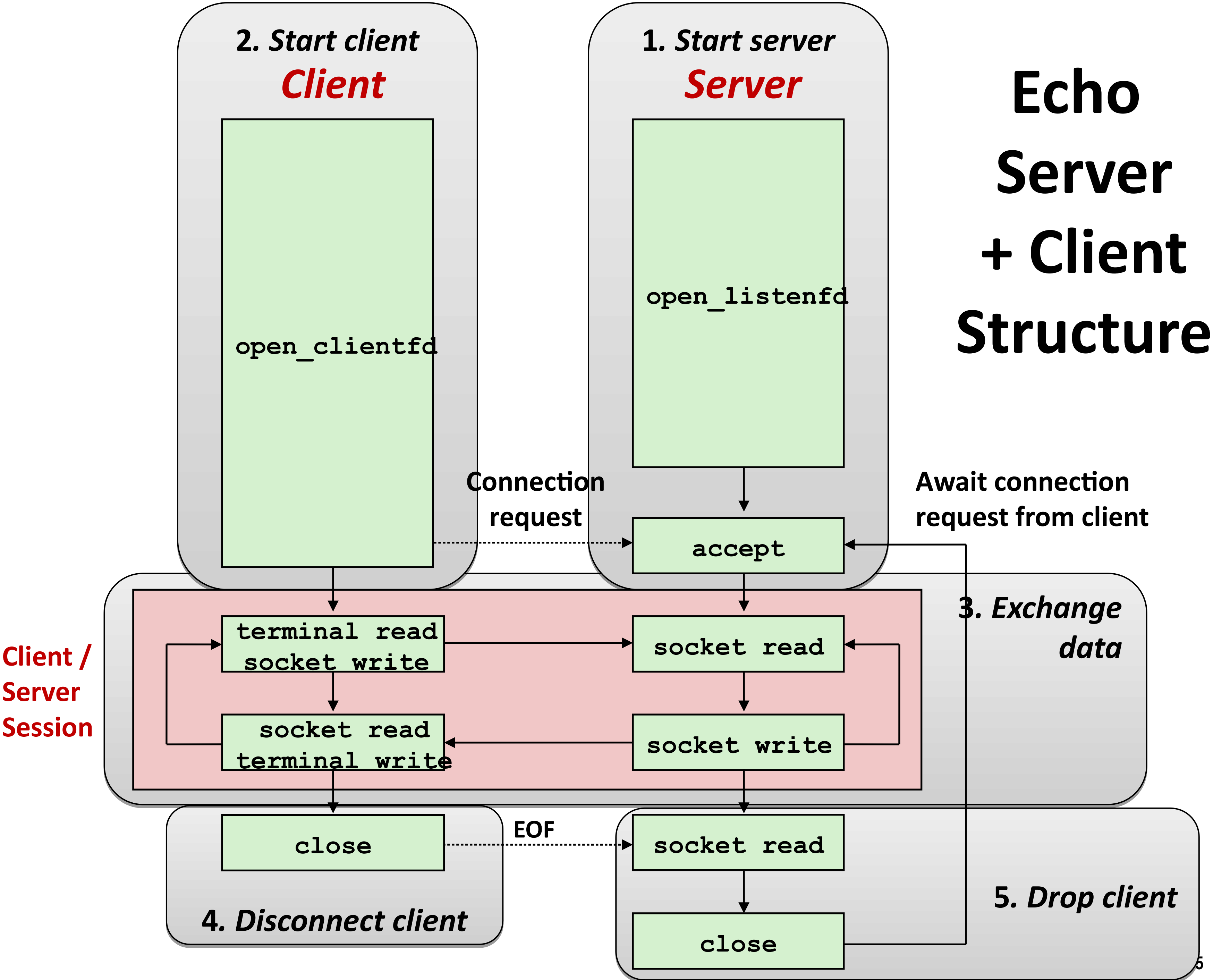


- **The main distinction between regular file I/O and socket I/O is how the application "opens" the socket descriptors**

Socket 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 Structure



2. *Start client*

Client

`open_clientfd`

1. *Start server*

Server

`open_listenfd`

Connection request

`accept`

Await connection request from client

Client / Server Session

3. *Exchange data*

`terminal read`
`socket write`

`socket read`

`socket read`
`terminal write`

`socket write`

`close`

EOF

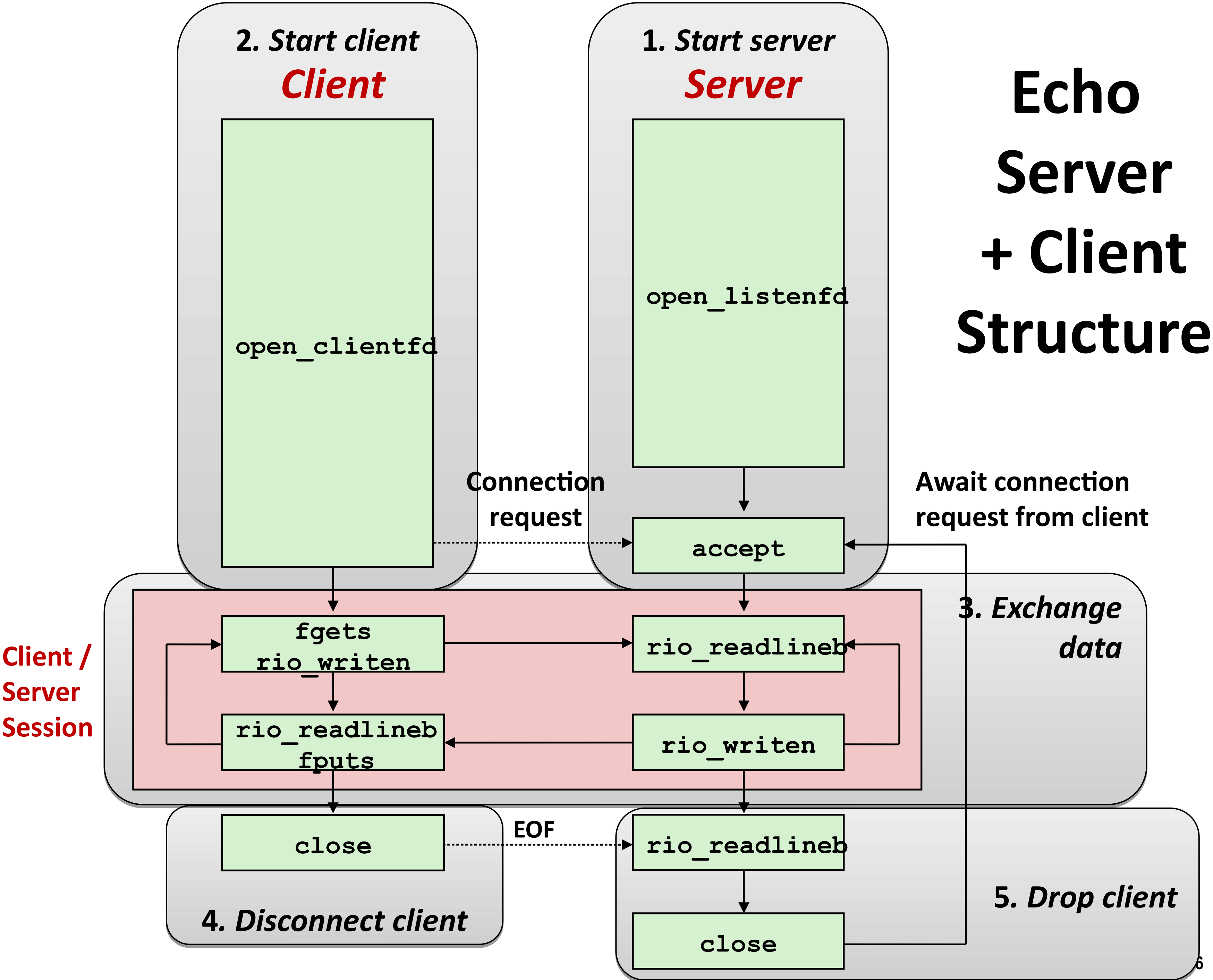
`socket read`

`close`

4. *Disconnect client*

5. *Drop client*

Echo Server + Client Structure



1. *Start server*

Server

`open_listenfd`

`accept`

Await connection request from client

2. *Start client*

Client

`open_clientfd`

Connection request

Client / Server Session

3. *Exchange data*

`fgets`
`rio_writen`

`rio_readlineb`

`rio_writen`

`rio_readlineb`
`fputs`

4. *Disconnect client*

`close`

EOF

5. *Drop client*

`rio_readlineb`

`close`

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

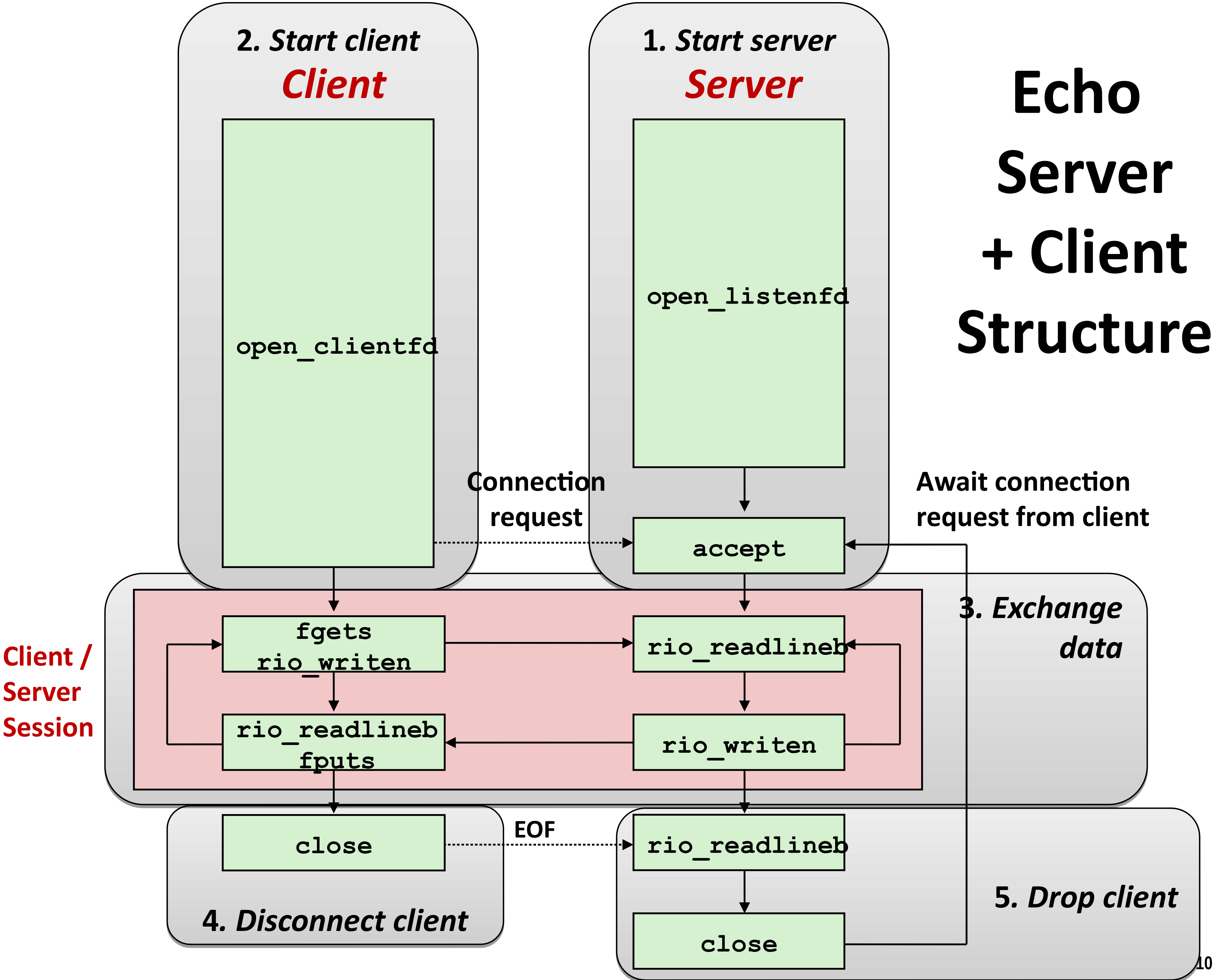
- `rio_readlineb` reads a *text line* of up to `maxlen` bytes from file `fd` and stores the line in `usrbuf`
  - Especially useful for reading text lines from network sockets
- Stopping conditions
  - `maxlen` bytes read
  - EOF encountered
  - Newline (‘`\n`’) encountered

Echo Client: Main Routine

```
#include "csapp.h"

int main(int argc, char **argv) {
  char *host = argv[1];
  char *port = argv[2];
  int clientfd = Open_clientfd(host, port);

  char buf[MAXLINE];
  rio_t rio;
  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

```c
#include "csapp.h”

void echo(int connfd);

int main(int argc, char **argv) {
  int listenfd, connfd;
  socklen_t clientlen;
  struct sockaddr_storage clientaddr; /* Enough room for any addr */

  char client_hostname[MAXLINE], client_port[MAXLINE];
  listenfd = Open_listenfd(argv[1]);
  while (1) {
    clientlen = sizeof(struct sockaddr_storage); /* Important! */
    connfd = Accept(listenfd, (SA *)&clientaddr, &clientlen);
    Getnameinfo((SA *) &clientaddr, clientlen,
                client_hostname, MAXLINE, client_port, MAXLINE, 0);
    printf("Connected to (%s, %s)\n", client_hostname, client_port);
    echo(connfd);
    Close(connfd);
  }
  exit(0);
}
```

echoserveri.c

Echo Server: echo function

- **The server uses RIO to read and echo text lines until EOF (end-of-file) condition is encountered.**
  - EOF condition caused by client calling **close(clientfd)**

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

  Rio_readinitb(&rio, connfd);
  while((n = Rio_readlineb(&rio, buf, MAXLINE)) != 0) {
    printf("server received %d bytes\n", (int)n);
    Rio_writen(connfd, buf, n);
  }
}
```

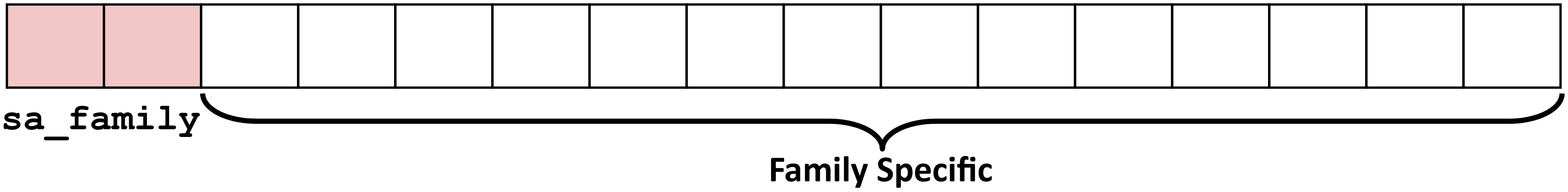
echo.c

Socket Address Structures & getaddrinfo

- **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.  */
};
```

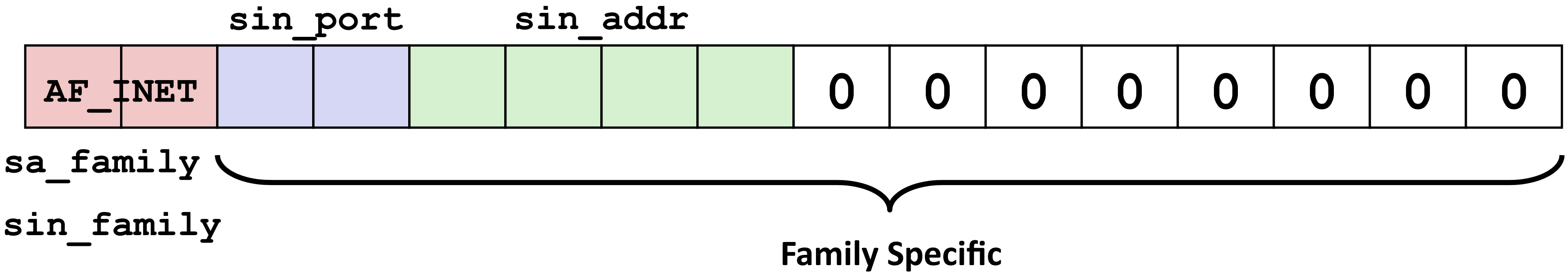


- **getaddrinfo** converts string representations of hostnames, host addresses, ports, service names to socket address structures

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

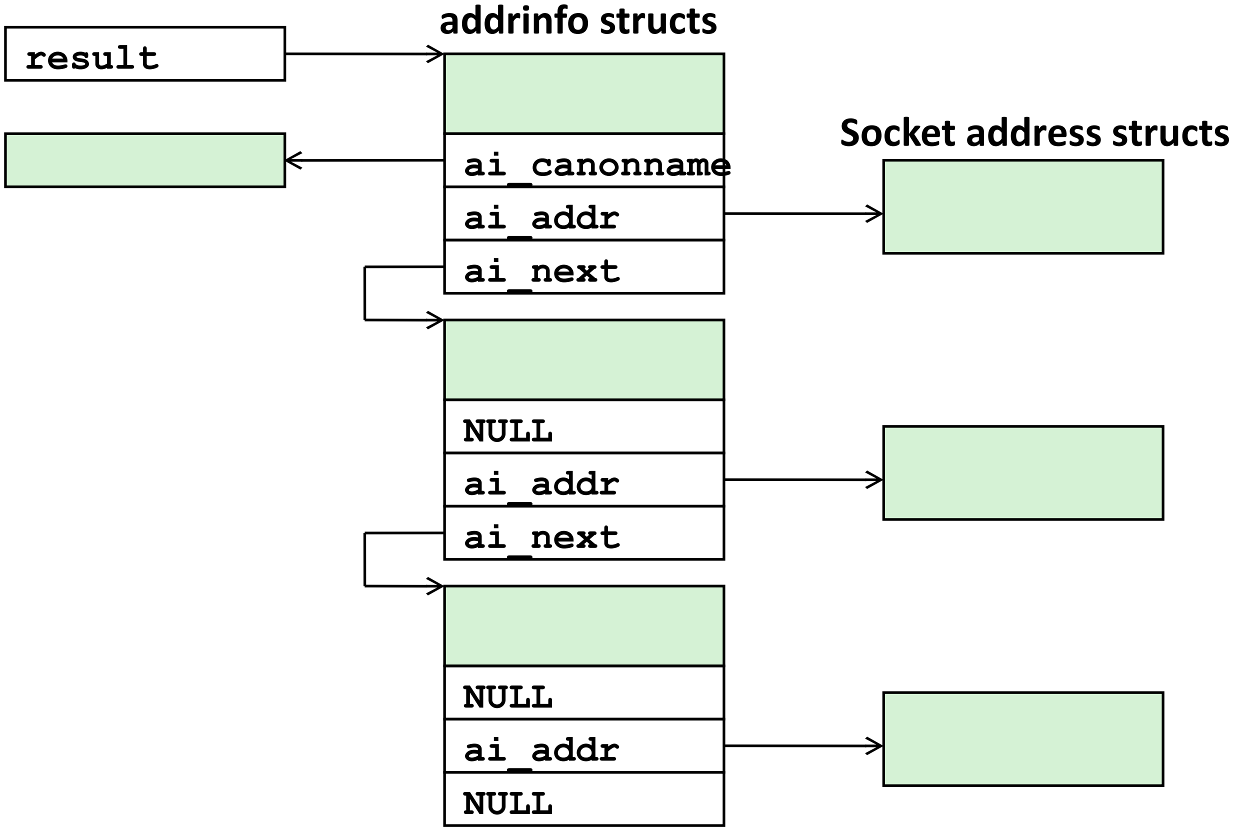
- **Disadvantages**
  - Somewhat complex
  - Fortunately, a small number of usage patterns suffice in most cases.

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



- 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

```c
#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);
}
```

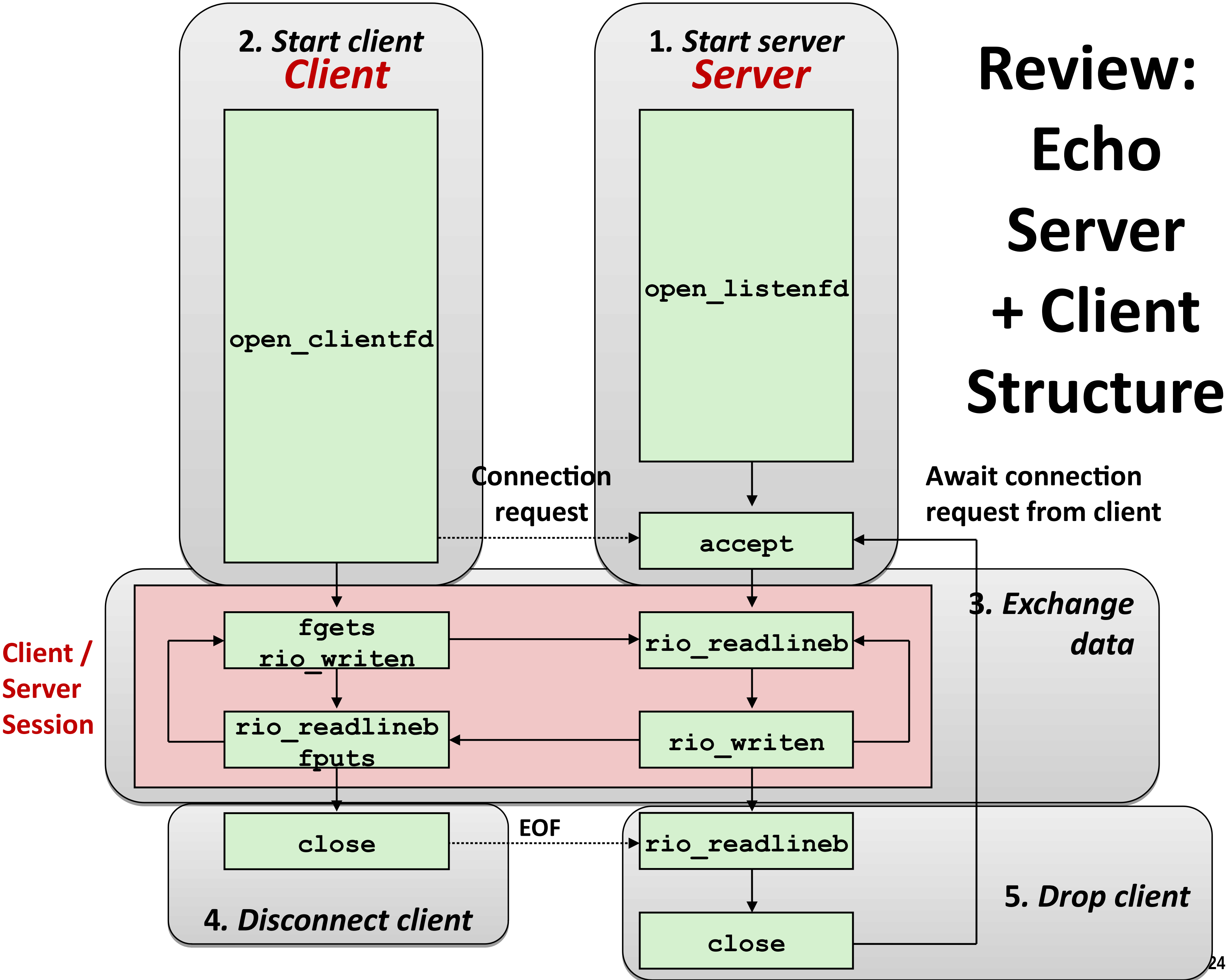
hostinfo.c

Running hostinfo

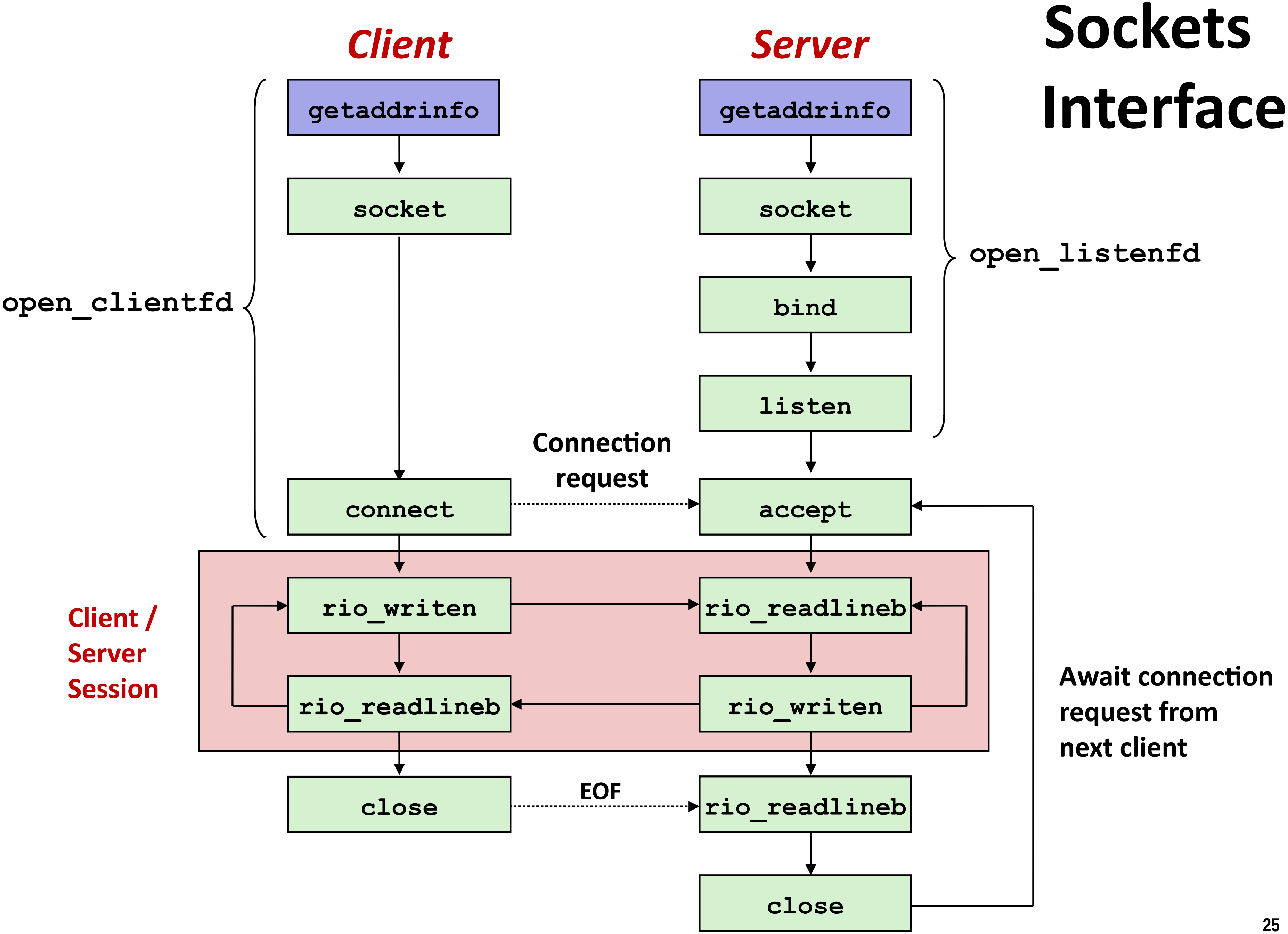
```
rocklobster> ./hostinfo localhost
127.0.0.1

rocklobster> ./hostinfo whaleshark.ics.cs.cmu.edu
128.2.210.175

rocklobster> ./hostinfo twitter.com
199.16.156.230
199.16.156.38
199.16.156.102
199.16.156.198

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

Network Programming: Part II

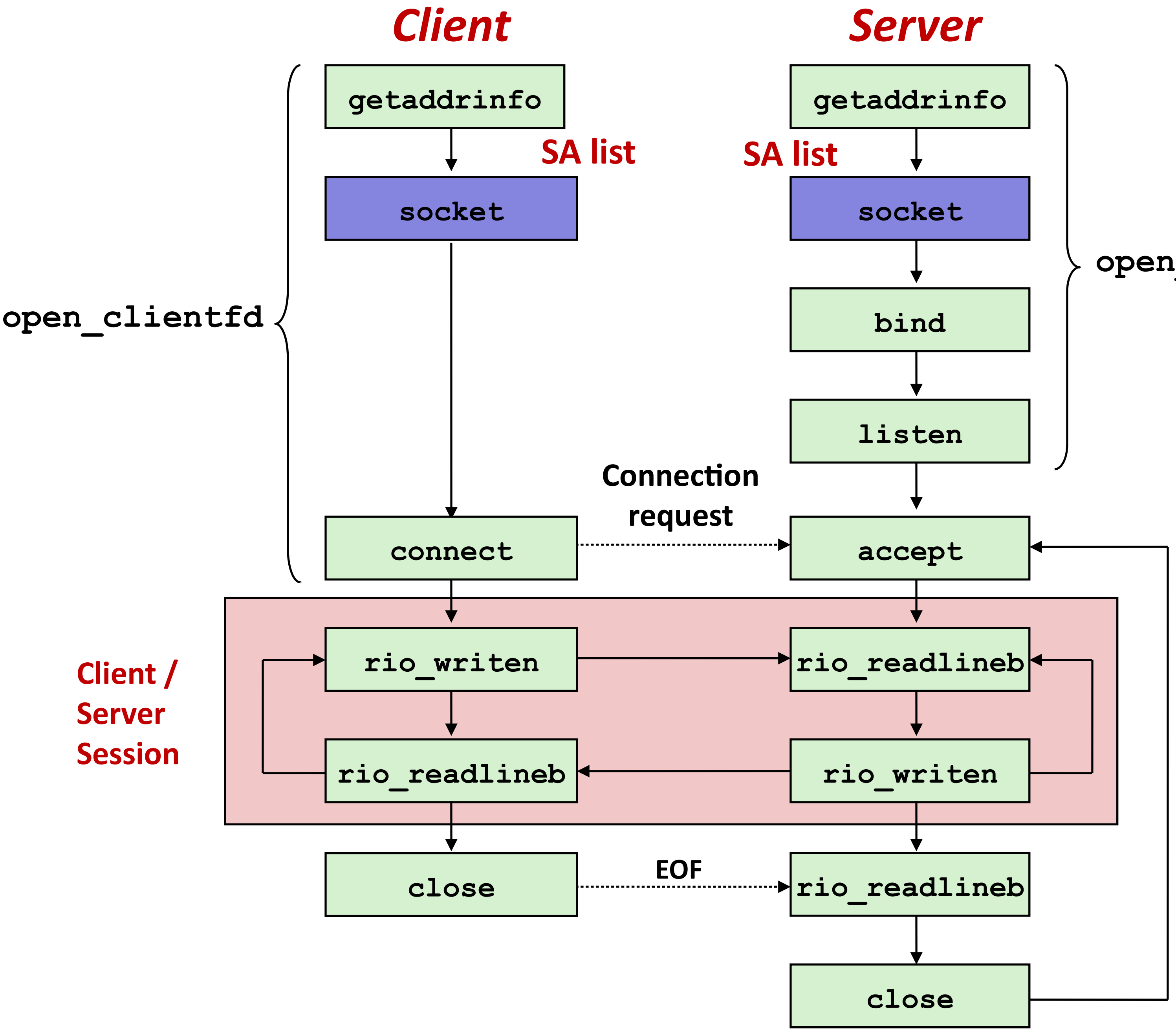
Review: Echo Server + Client Structure



Sockets Interface



Sockets Interface



Await connection request from next client

Sockets Interface: `socket`

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

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

- Example:

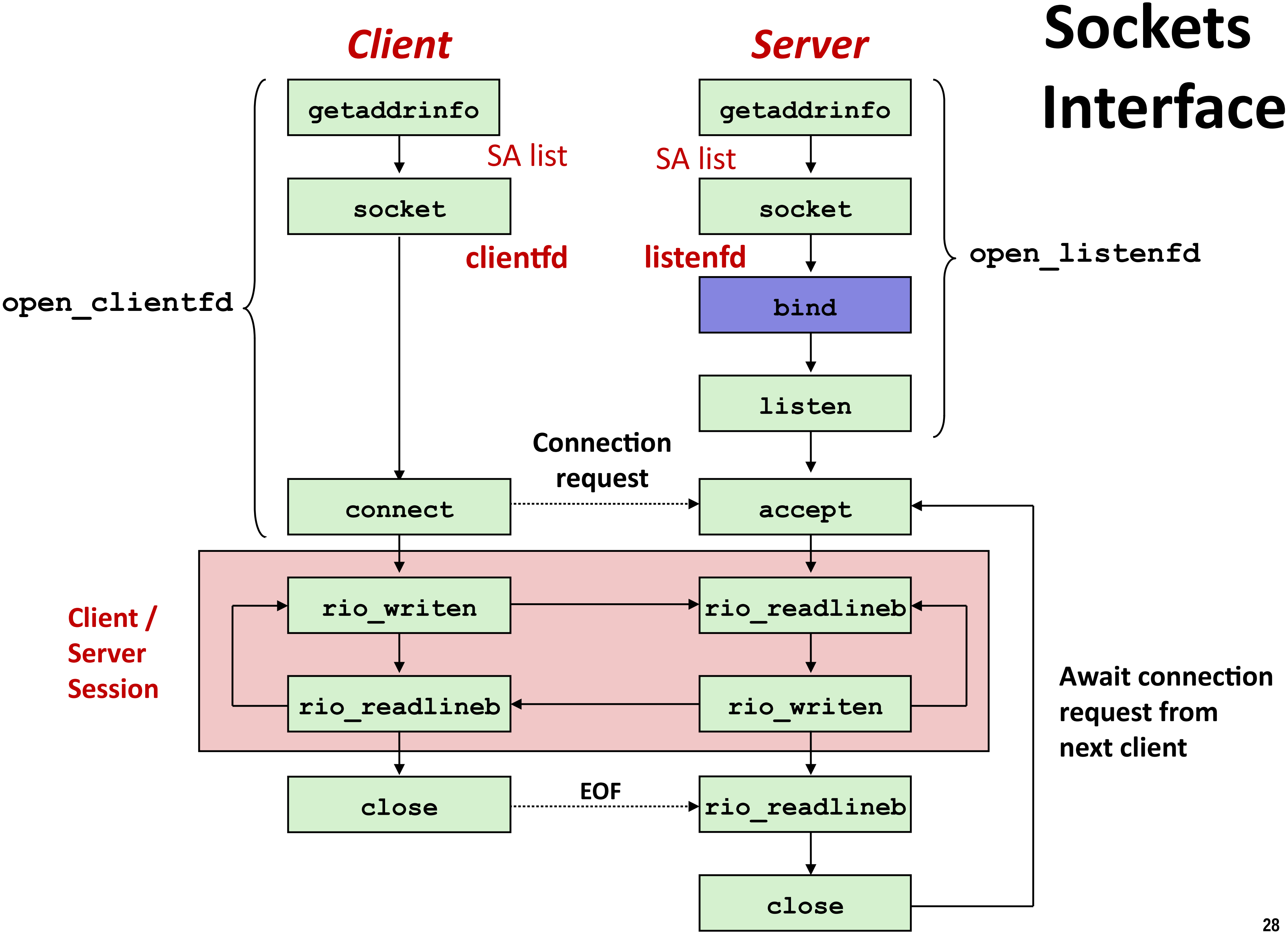
```
int clientfd = socket(AF_INET, SOCK_STREAM, 0);
```

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:

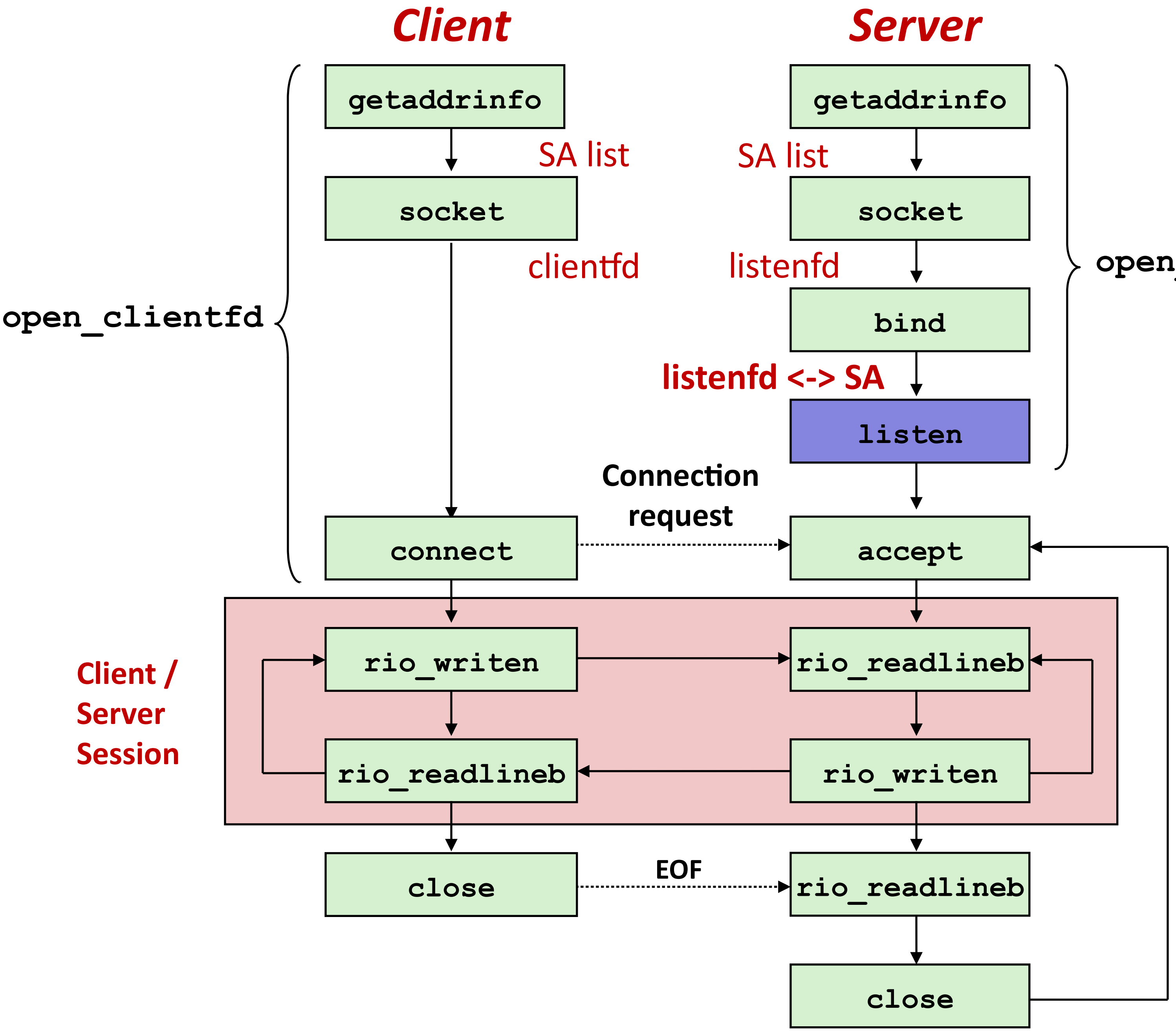
```
int bind(int sockfd, SA *addr, socklen_t addrlen);
```

Recall: `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



Await connection request from next client

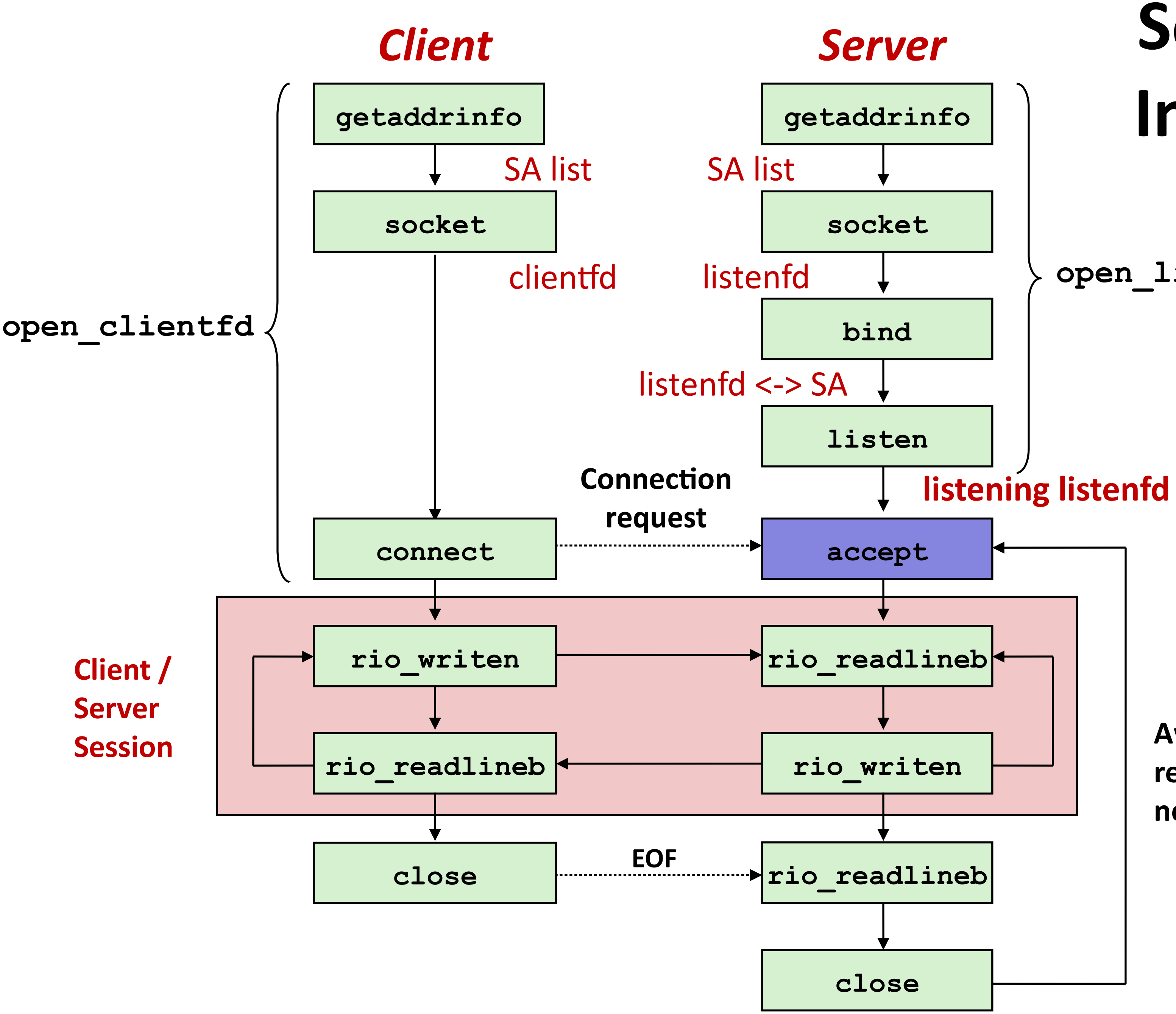
Sockets Interface: `listen`

- 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



Await connection request from next client

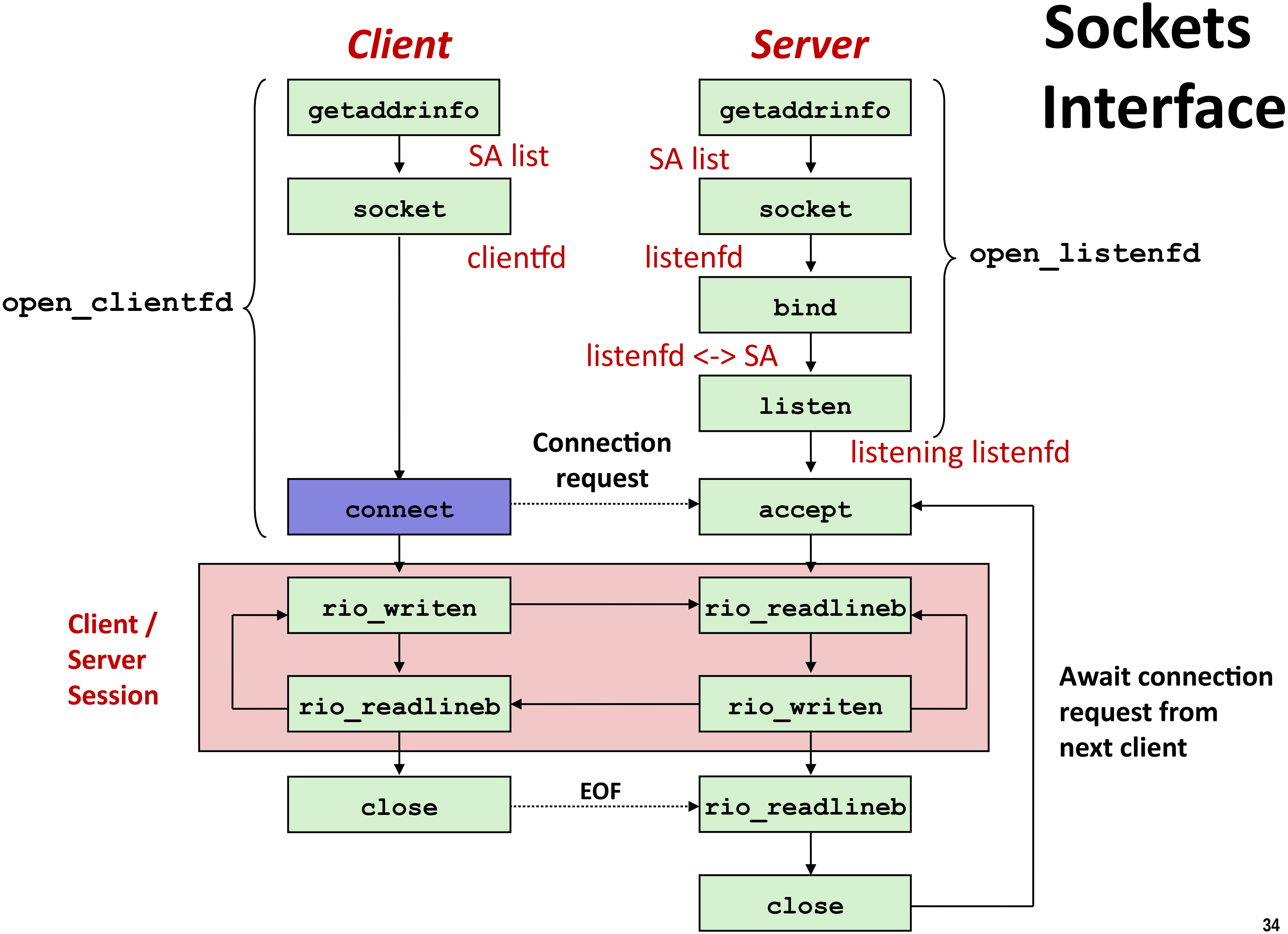
Sockets Interface: `accept`

- 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



Client

Server

open_clientfd

getaddrinfo

SA list

socket

clientfd

connect

open_listenfd

getaddrinfo

SA list

socket

listenfd

bind

listenfd <-> SA

listen

listening listenfd

Connection request

accept

Client / Server Session

rio_writen

rio_readlineb

rio_readlineb

rio_writen

close

EOF

rio_readlineb

close

Await connection request from next client

Sockets Interface: connect

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

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

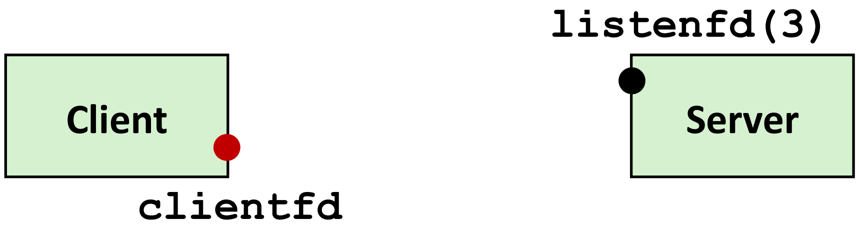
- **Attempts to establish a connection with server at socket address addr**
  - If successful, then **clientfd** is now ready for reading and writing.
  - Resulting connection is characterized by socket pair

    (**x:y, addr.sin_addr:addr.sin_port**)

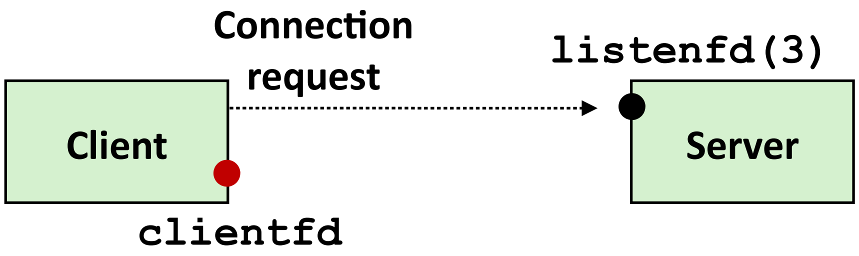
    - **x** is client address
    - **y** is ephemeral port that uniquely identifies client process on client host

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

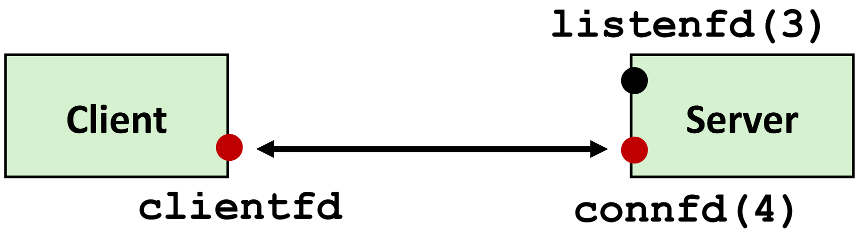
connect/accept Illustrated



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

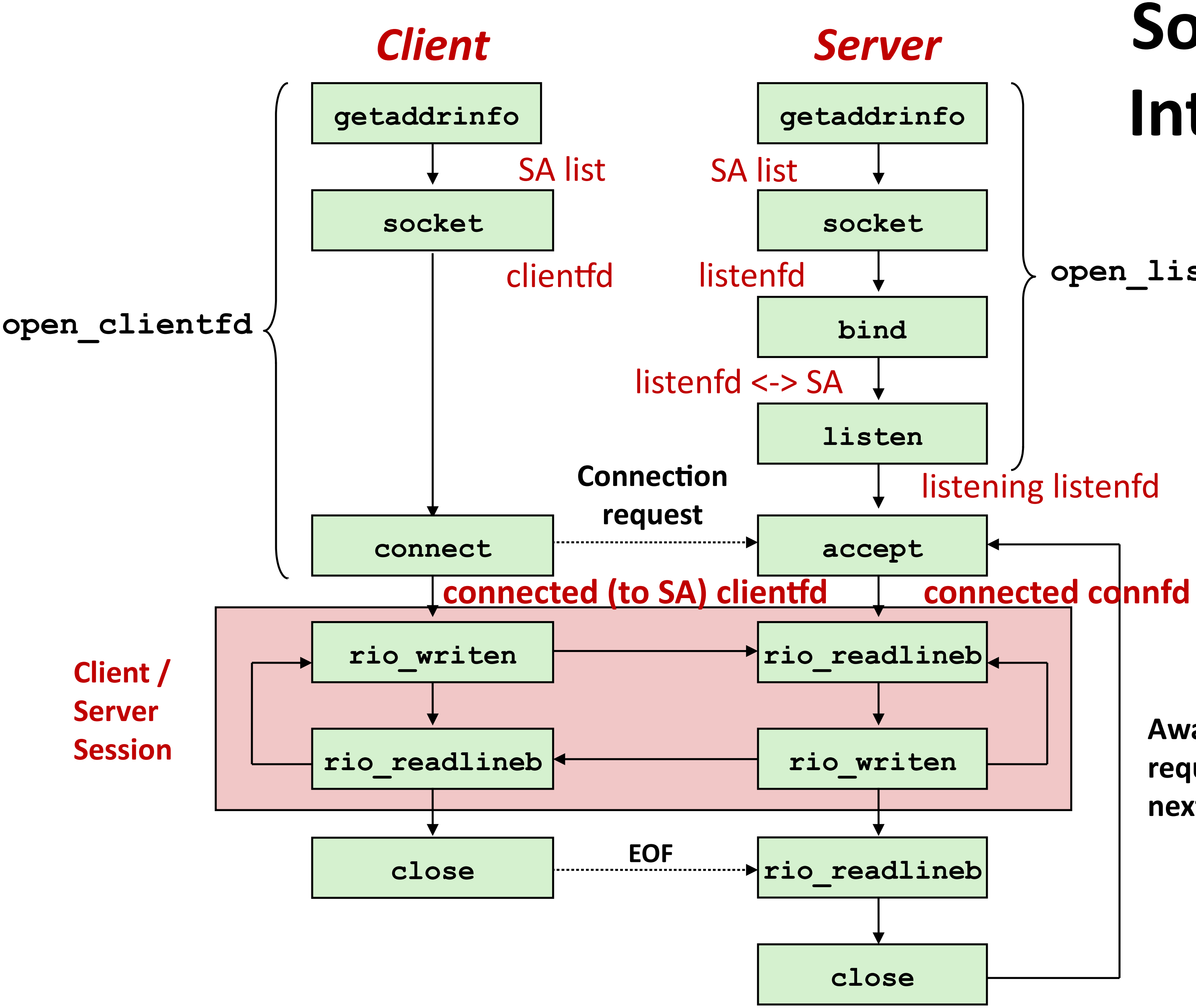
Connected vs. Listening Descriptors

- **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

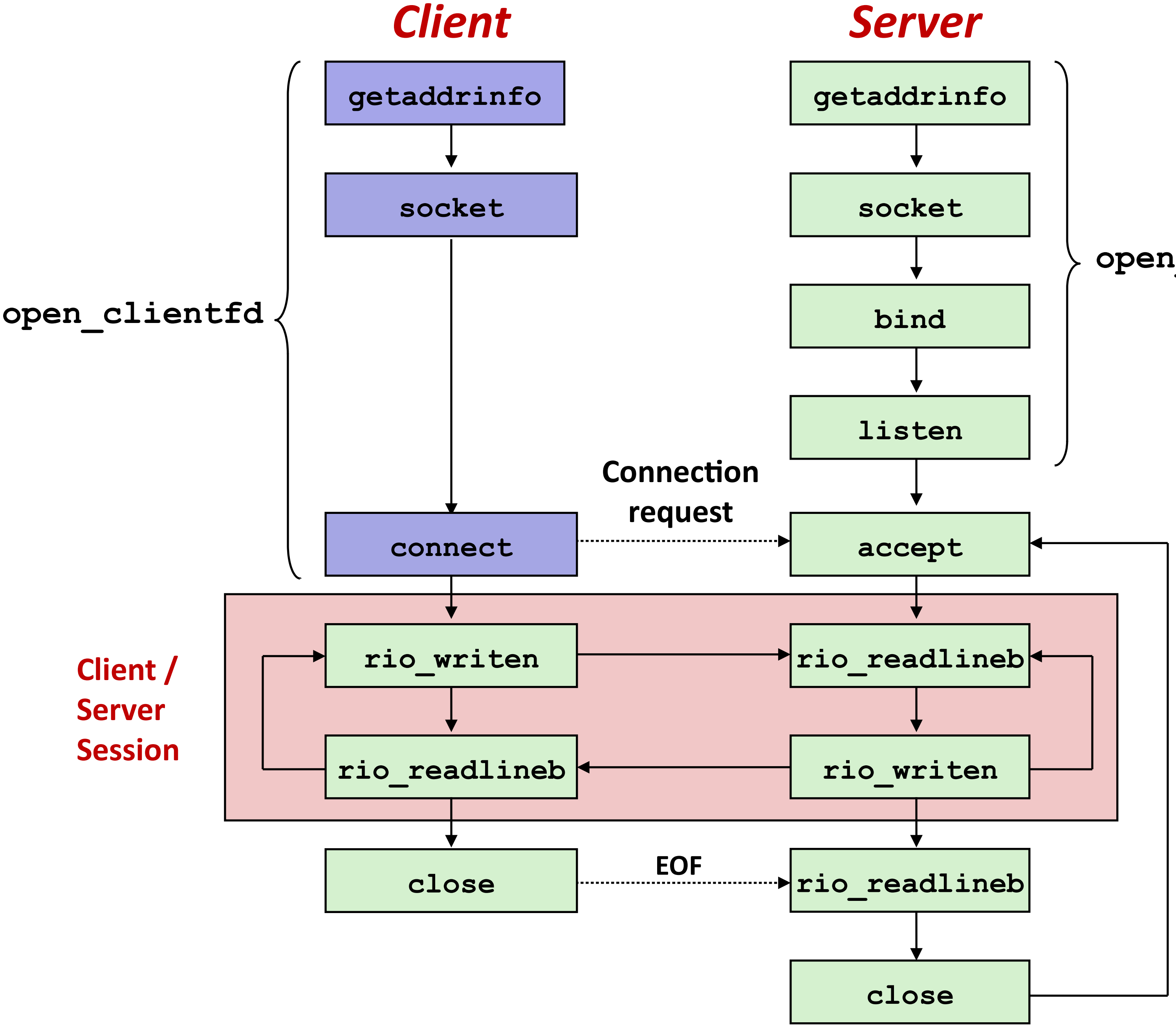
- **Why the distinction?**
  - Allows for concurrent servers that can communicate over many client connections simultaneously
    - E.g., Each time we receive a new request, we fork a child to handle the request

Sockets Interface



Await connection request from next client

Sockets Interface



Await connection request from next client

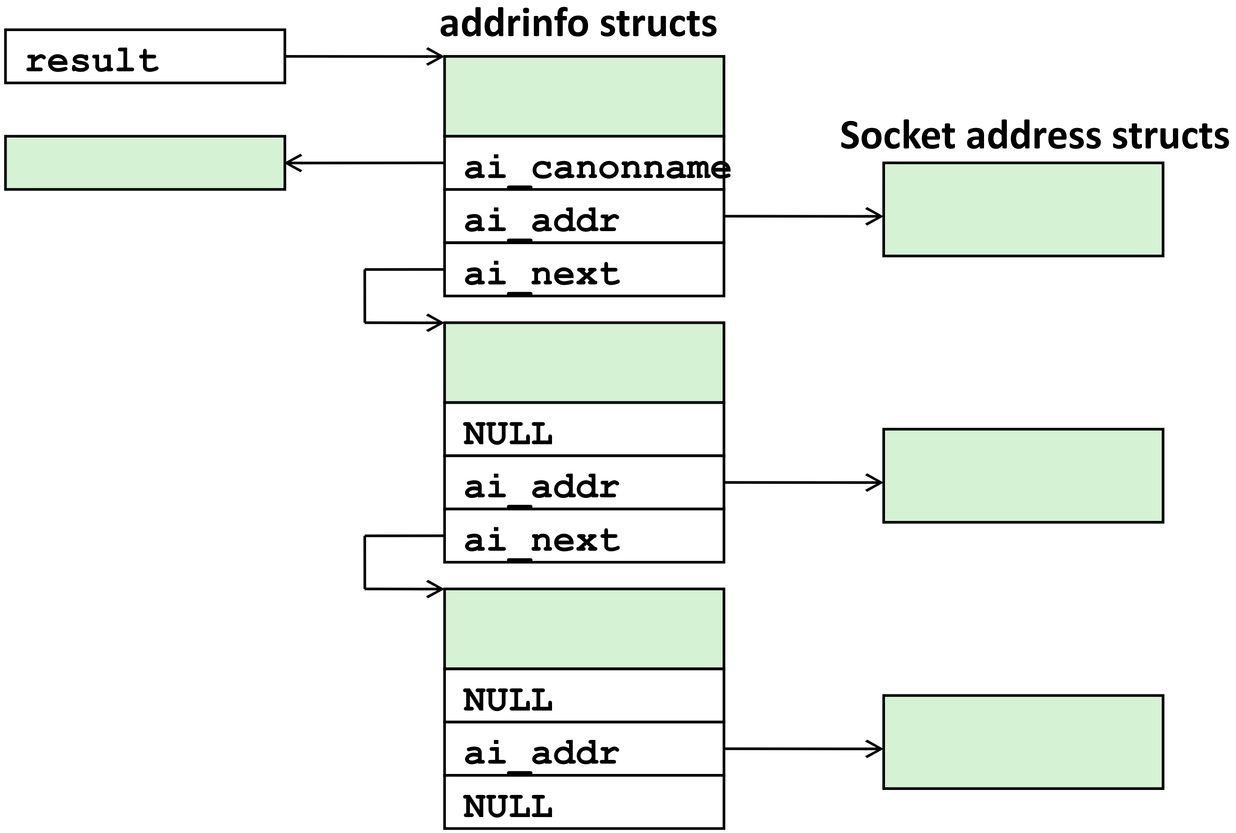
Sockets Helper: open_clientfd

- Establish a connection with a server

```c
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

Review: `getaddrinfo` Linked List



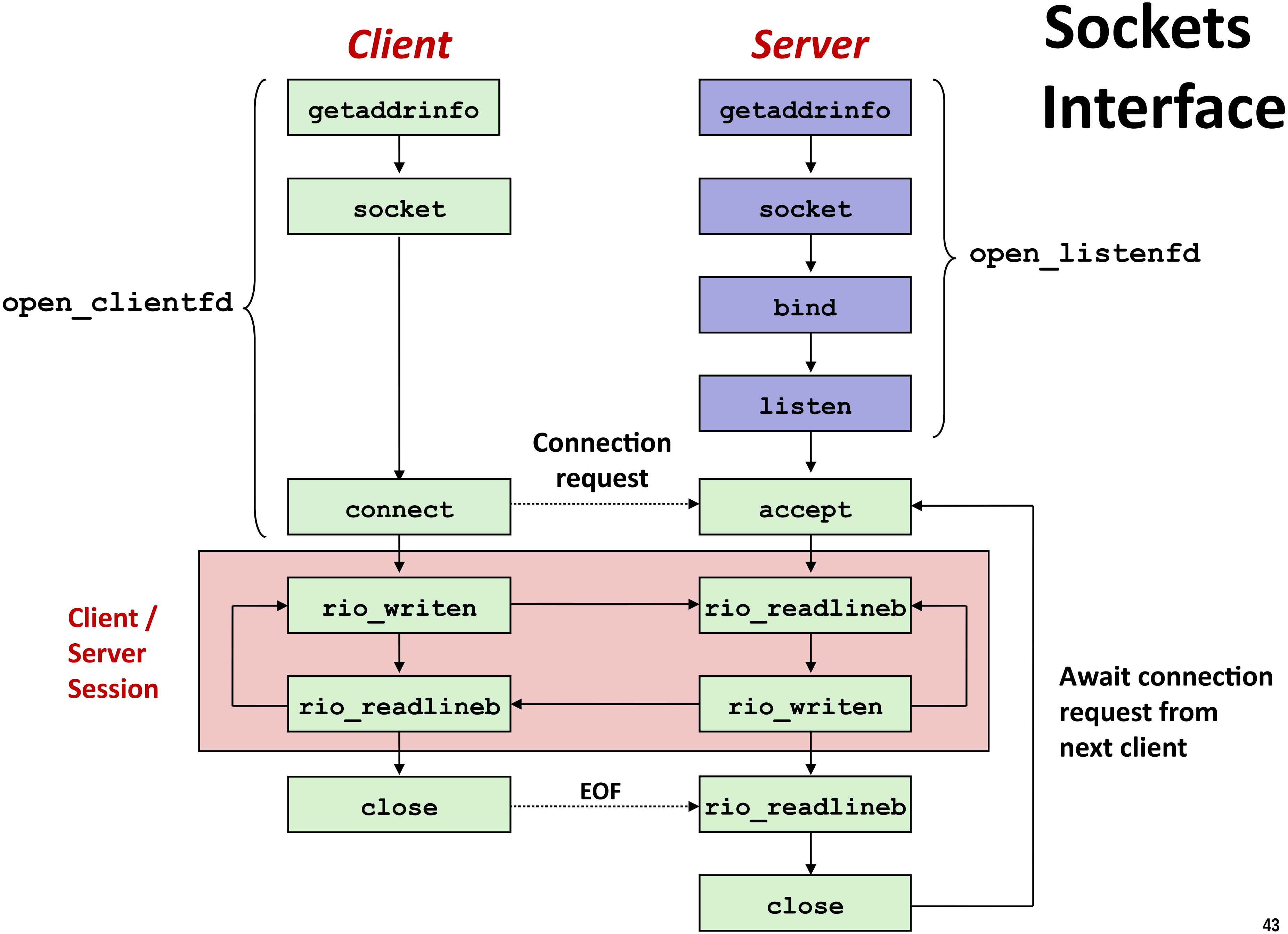
- Clients: walk this list, trying each socket address in turn, until the calls to `socket` and `connect` succeed.
- Servers: walk the list until calls to `socket` and `bind` succeed.

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

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

Sockets Helper: `open_listenfd` (cont)

```c
    /* 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.