EE309 Advanced Programming Techniques for EE

Lecture 13: Network programming 2

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[Slides from 15-213: Introduction to Computer Systems at CMU]

Today

- **Material we didn't get to yesterday**
  - Transmitting data using sockets
  - Socket addresses
  - `getaddrinfo`
- **Setting up connections**
- **Application protocol example: HTTP**

Sockets

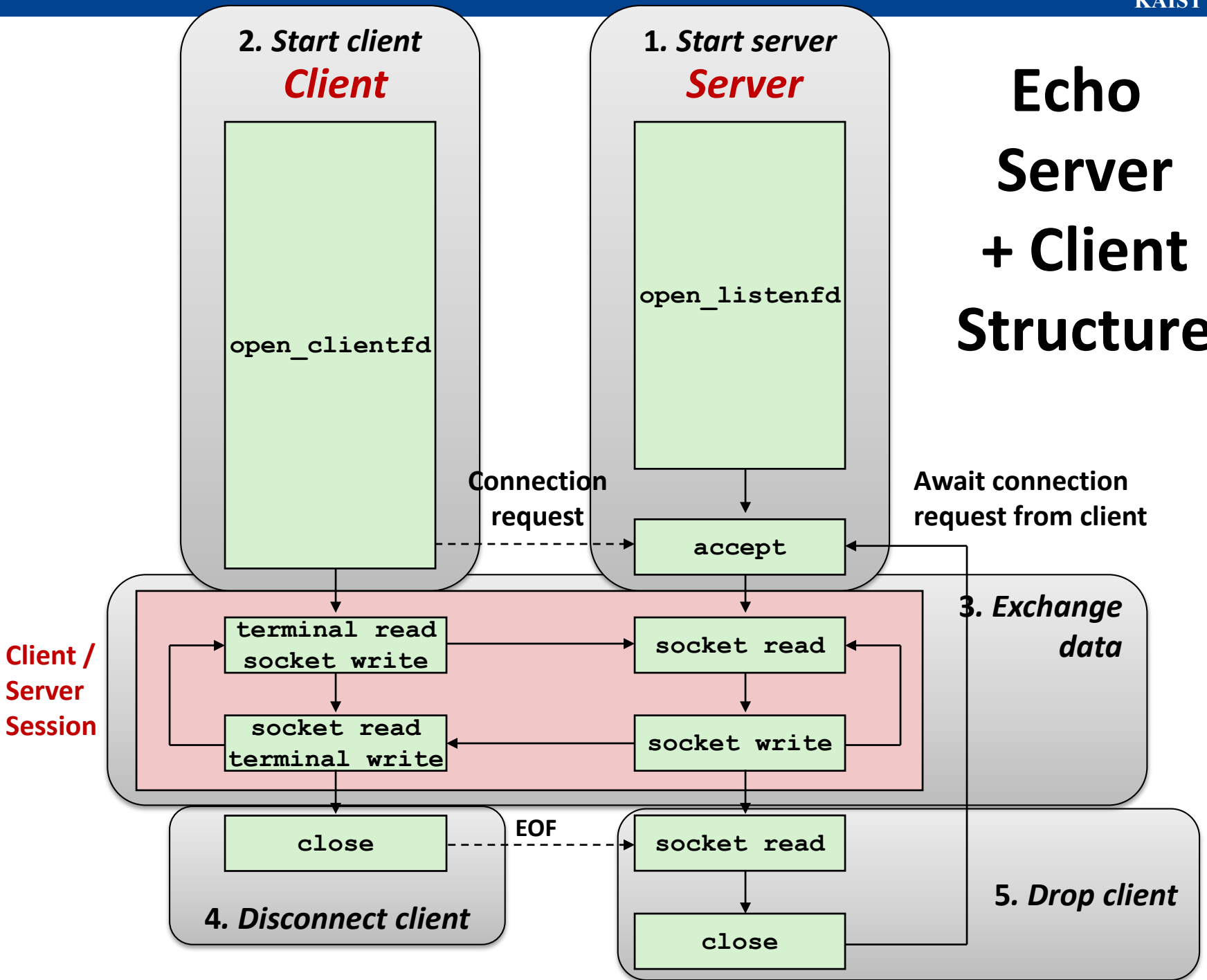
- **What is a socket?**
  - To the kernel, a socket is an endpoint of communication
  - To an application, a socket is a file descriptor that lets the application read/write from/to the network
  - Using the FD abstraction lets you reuse code & interfaces
- **Clients and servers communicate with each 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



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**

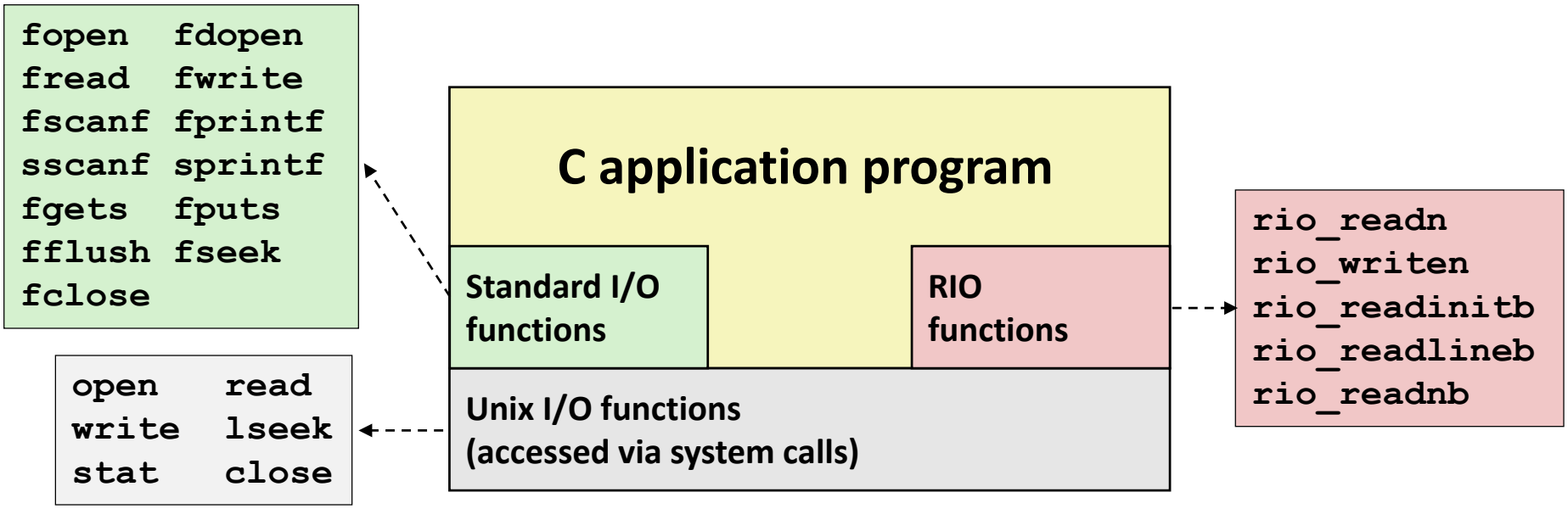
```
#include "csapp.h"

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

Today: Unix I/O, C Standard I/O, and RIO

- **Two *incompatible* libraries building on Unix I/O**
- **Robust I/O (RIO): 213 special wrappers**
  good coding practice: handles error checking, signals, and "short counts"



The RIO Package (213/CS:APP Package)

- **RIO is a set of wrappers that provide efficient and robust I/O in apps, such as network programs that are subject to short counts**
- **RIO provides two different kinds of functions**
  - Unbuffered input and output of binary data
    - **`rio_readn`** and **`rio_writen`**
  - Buffered input of text lines and binary data
    - **`rio_readlineb`** and **`rio_readnb`**
    - Buffered RIO routines are thread-safe and can be interleaved arbitrarily on the same descriptor

- **Download from http://csapp.cs.cmu.edu/3e/code.html**

  → **`src/csapp.c`** and **`include/csapp.h`**

Implementation of `rio_readn`

```
/*
 * rio_readn - Robustly read n bytes (unbuffered)
 */
ssize_t rio_readn(int fd, void *usrbuf, size_t n)
{
    size_t nleft = n;
    ssize_t nread;
    char *bufp = usrbuf;

    while (nleft > 0) {
        if ((nread = read(fd, bufp, nleft)) < 0) {
            if (errno == EINTR) /* Interrupted by sig handler return */
                nread = 0;      /* and call read() again */
            else
                return -1;      /* errno set by read() */
        }
        else if (nread == 0)
            break;              /* EOF */
        nleft -= nread;
        bufp += nread;
    }
    return (n - nleft);         /* Return >= 0 */
}
```

csapp.c

Echo Client: Main Routine

```c
#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: `echo` function

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

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

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

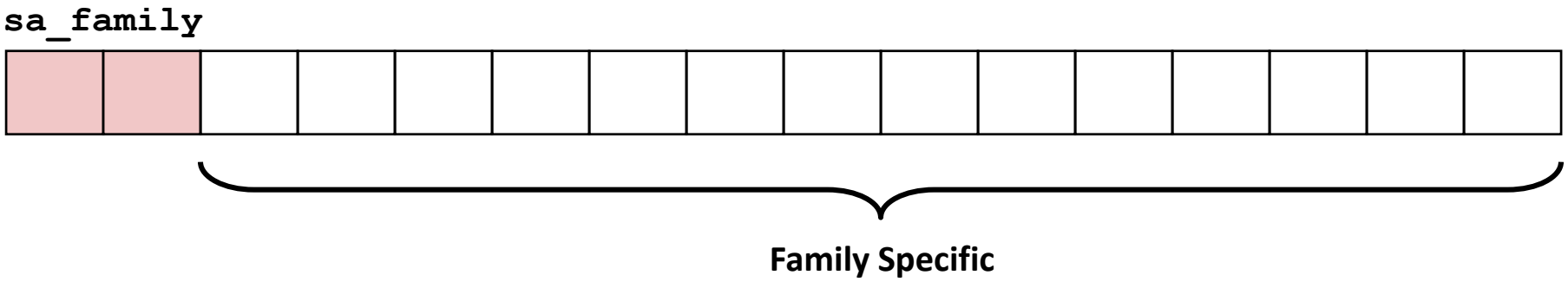
echo.c

Socket Address Structures

- **Generic socket address:**
  - For address arguments to **`connect`**, **`bind`**, and **`accept`** *(next lecture)*
  - In C++ this would be an abstract base class
  - For casting convenience, we adopt the Stevens convention:

    `typedef struct sockaddr SA;`

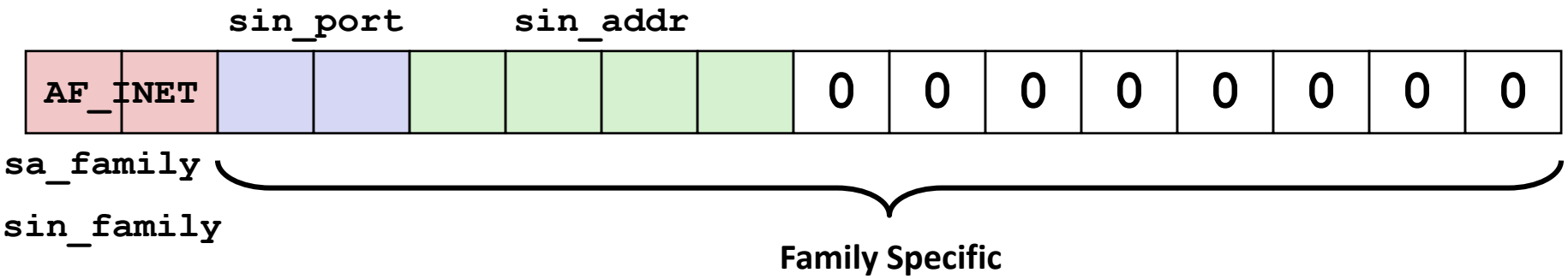
```
struct sockaddr {
  uint16_t  sa_family;    /* Protocol family */
  char      sa_data[14];  /* Address data  */
};
```



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

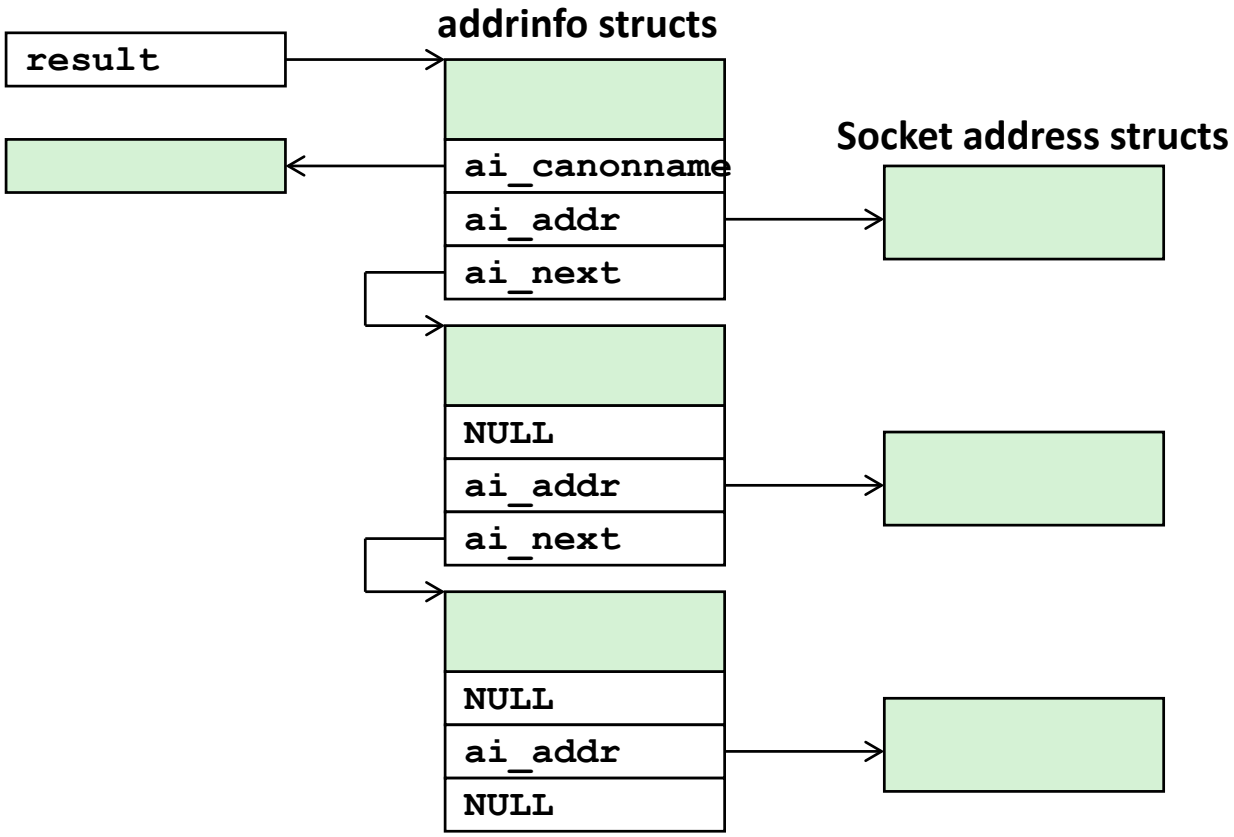
- **Disadvantages**
  - Somewhat complex
  - Fortunately, a small number of usage patterns suffice in most cases.

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 .

(**`socket`**, **`connect`**, **`bind`** to be discussed next)

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);
}
```

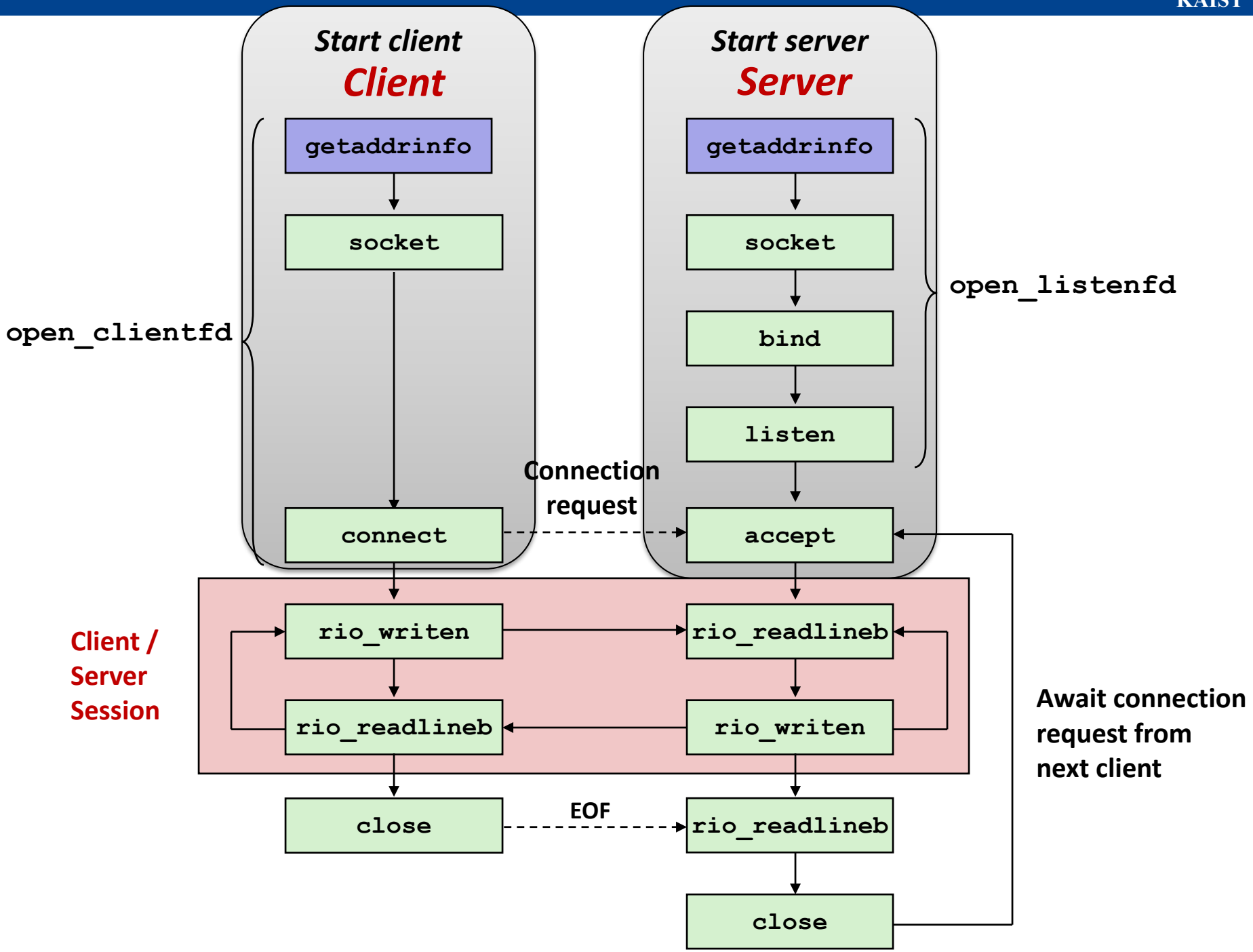
hostinfo.c

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
```

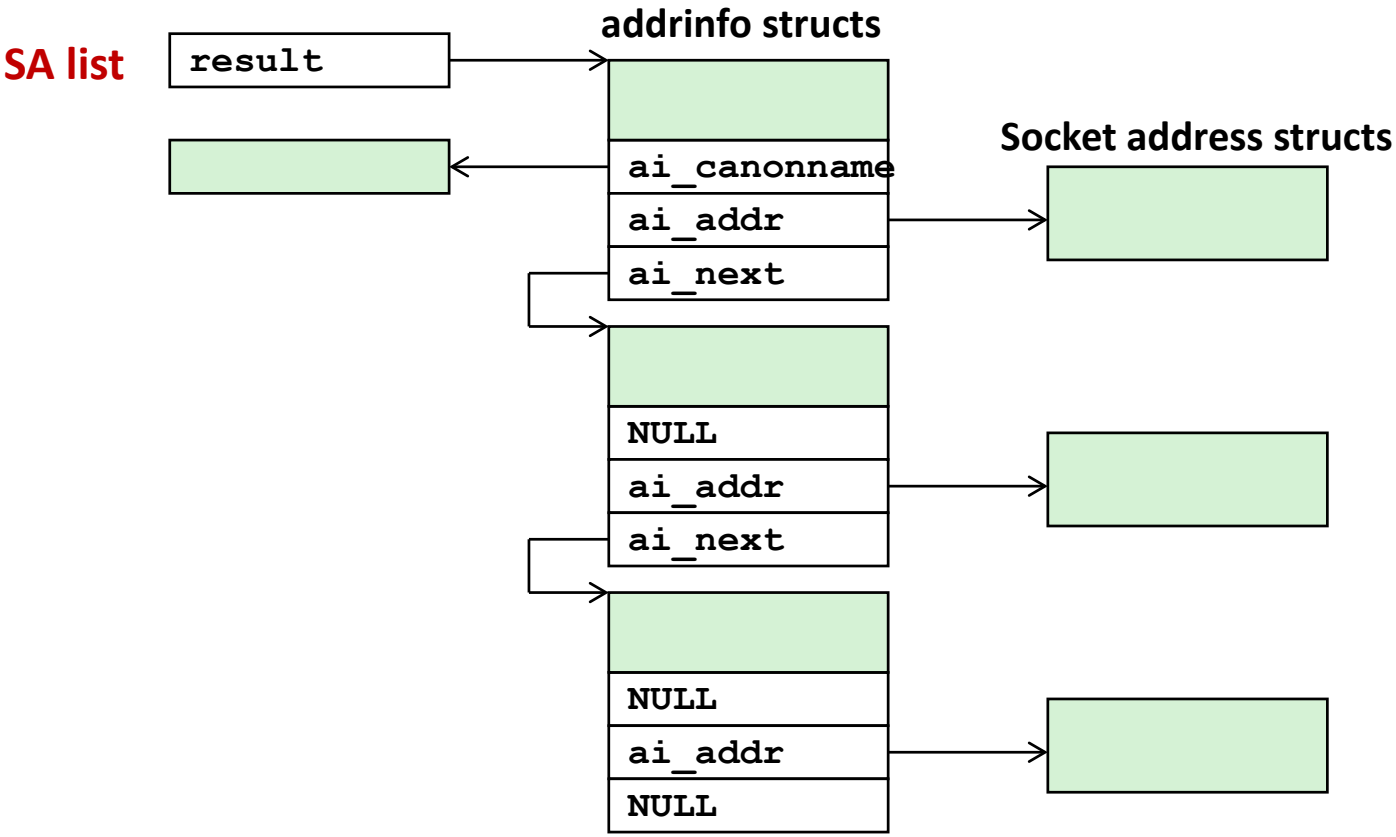
Today

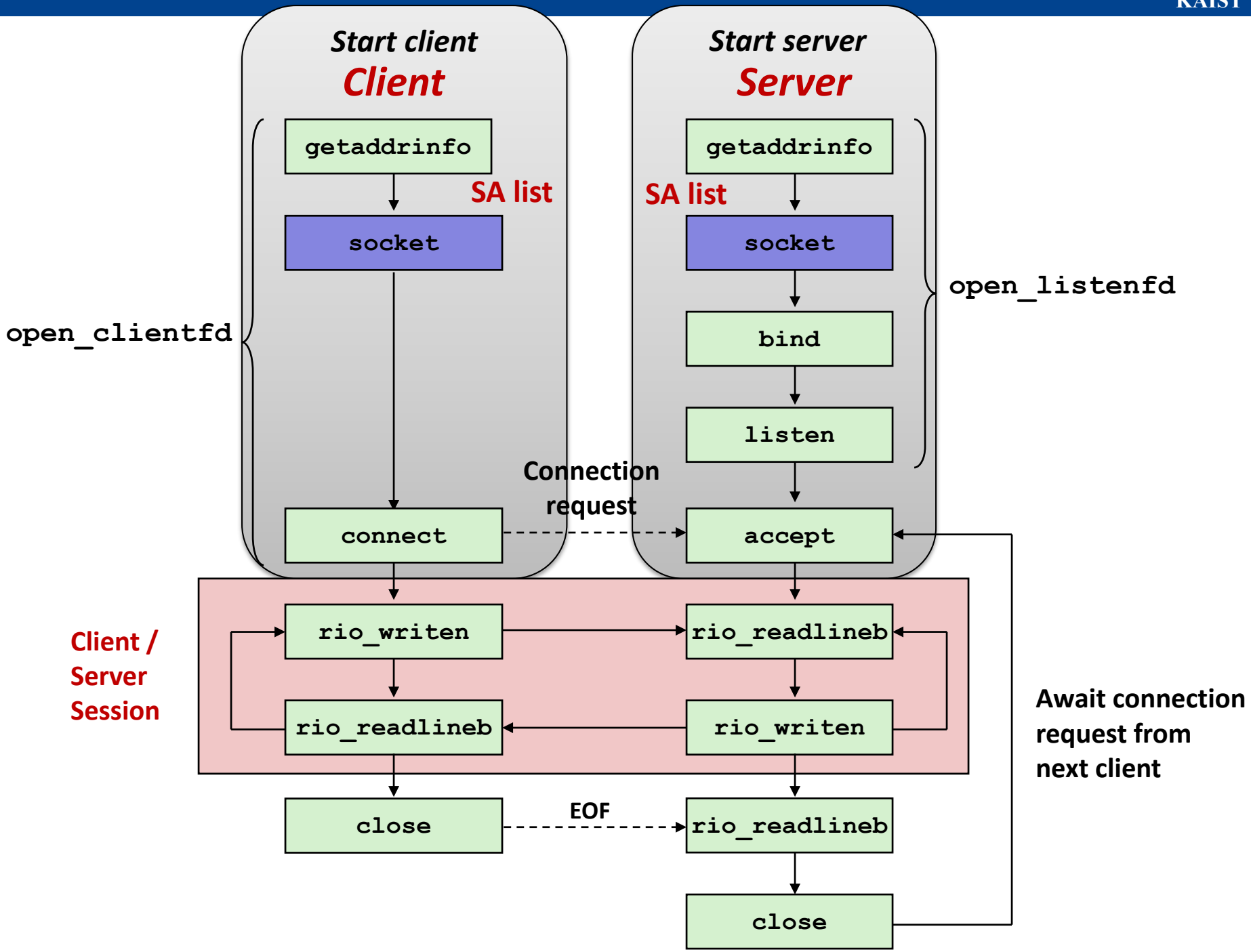
- Questions from yesterday
- Material we didn't get to yesterday
  - Transmitting data using sockets
  - Socket addresses
  - `getaddrinfo`
- **Setting up connections**
- Application protocol example: HTTP


Start client
Client
Start server
Server
getaddrinfo
socket
bind
listen
connect
accept
open_clientfd
open_listenfd
Connection request
rio_writen
rio_readlineb
rio_readlineb
rio_writen
Client / Server Session
close
EOF
rio_readlineb
close
Await connection request from next client

Review: `getaddrinfo`

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




Start client
Client
Start server
Server
getaddrinfo
SA list
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open_clientfd
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Connection request
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Client / Server Session
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rio_readlineb
rio_readlineb
rio_writen
close
EOF
rio_readlineb
close
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);
```

Protocol specific!

Indicates that we are using 32-bit IPV4 addresses

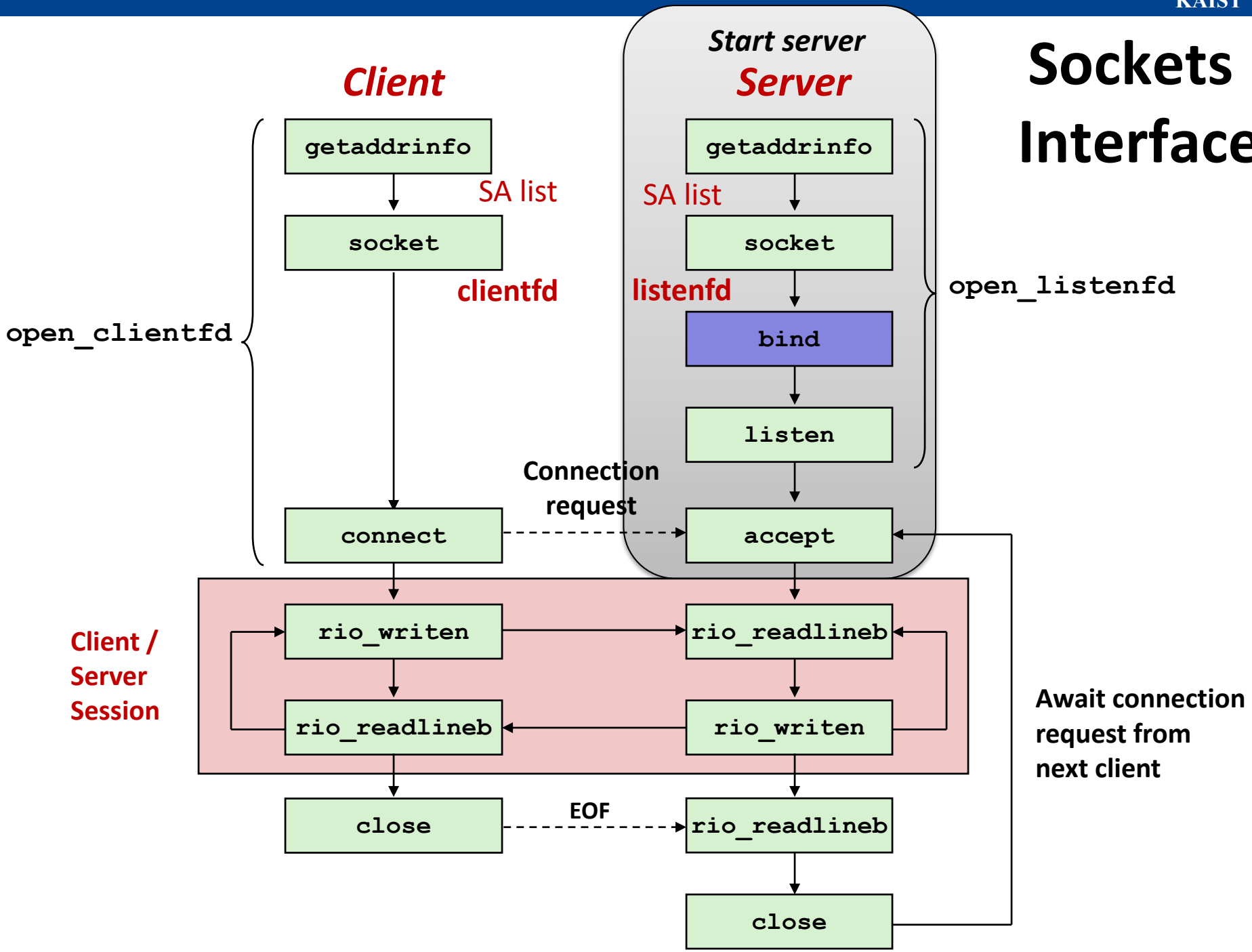
Indicates that the socket will be the end point of a reliable (TCP) connection

- Example:

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

Use getaddrinfo and you don't have to know or care which protocol!

Sockets Interface



Sockets Interface: `bind`

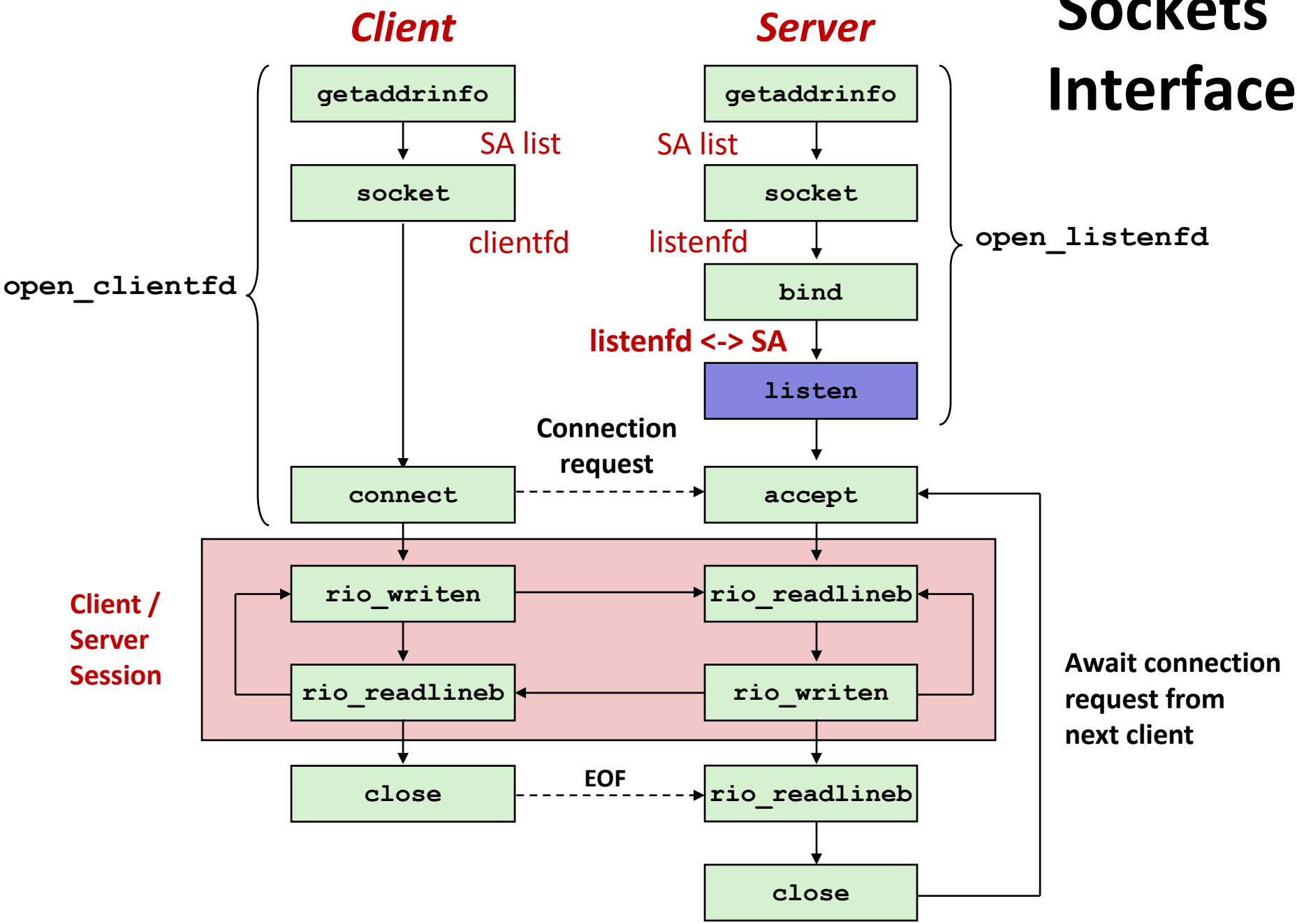
- A server uses `bind` to ask the kernel to associate the server's socket address with a socket descriptor:

```
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`

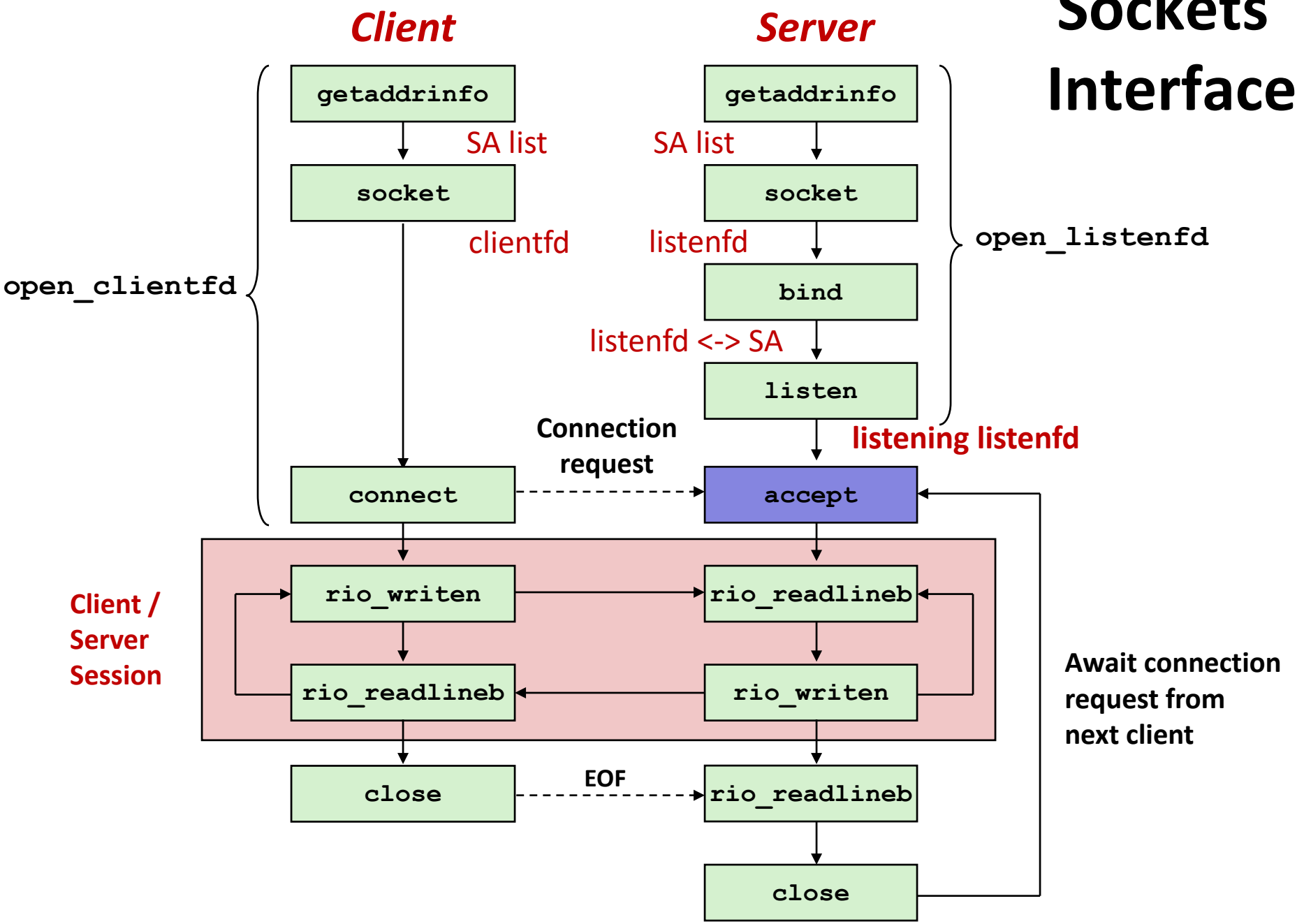
- Kernel assumes that descriptor from socket function is an *active socket* that will be on the client end
- A server calls the listen function to tell the kernel that a descriptor will be used by a server rather than a client:

```
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`

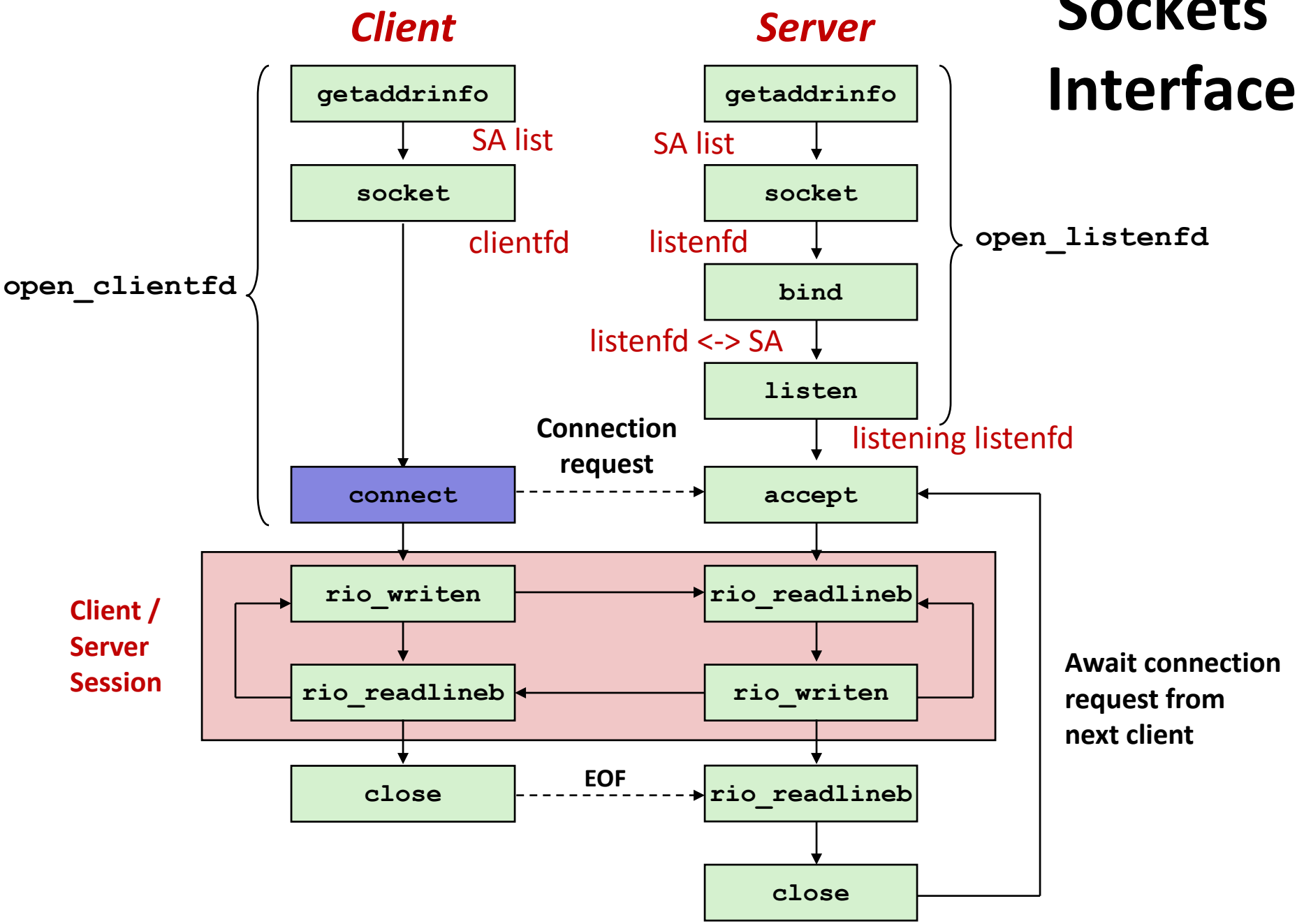
- Servers wait for connection requests from clients by calling `accept`:

```
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`:**

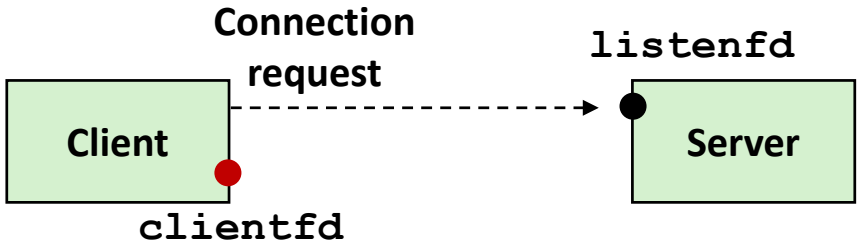
```
int connect(int clientfd, SA *addr, socklen_t addrlen);
```

- **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`

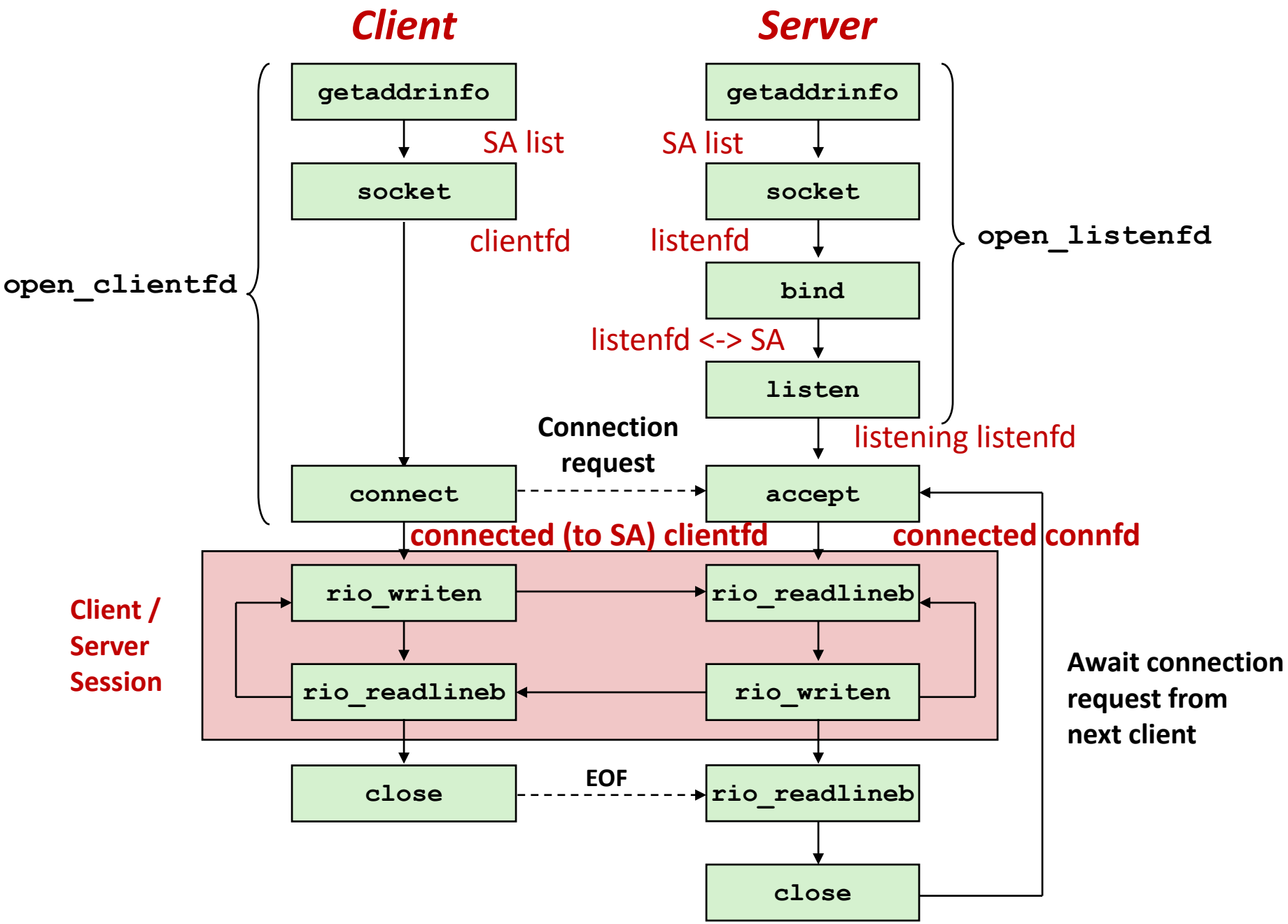


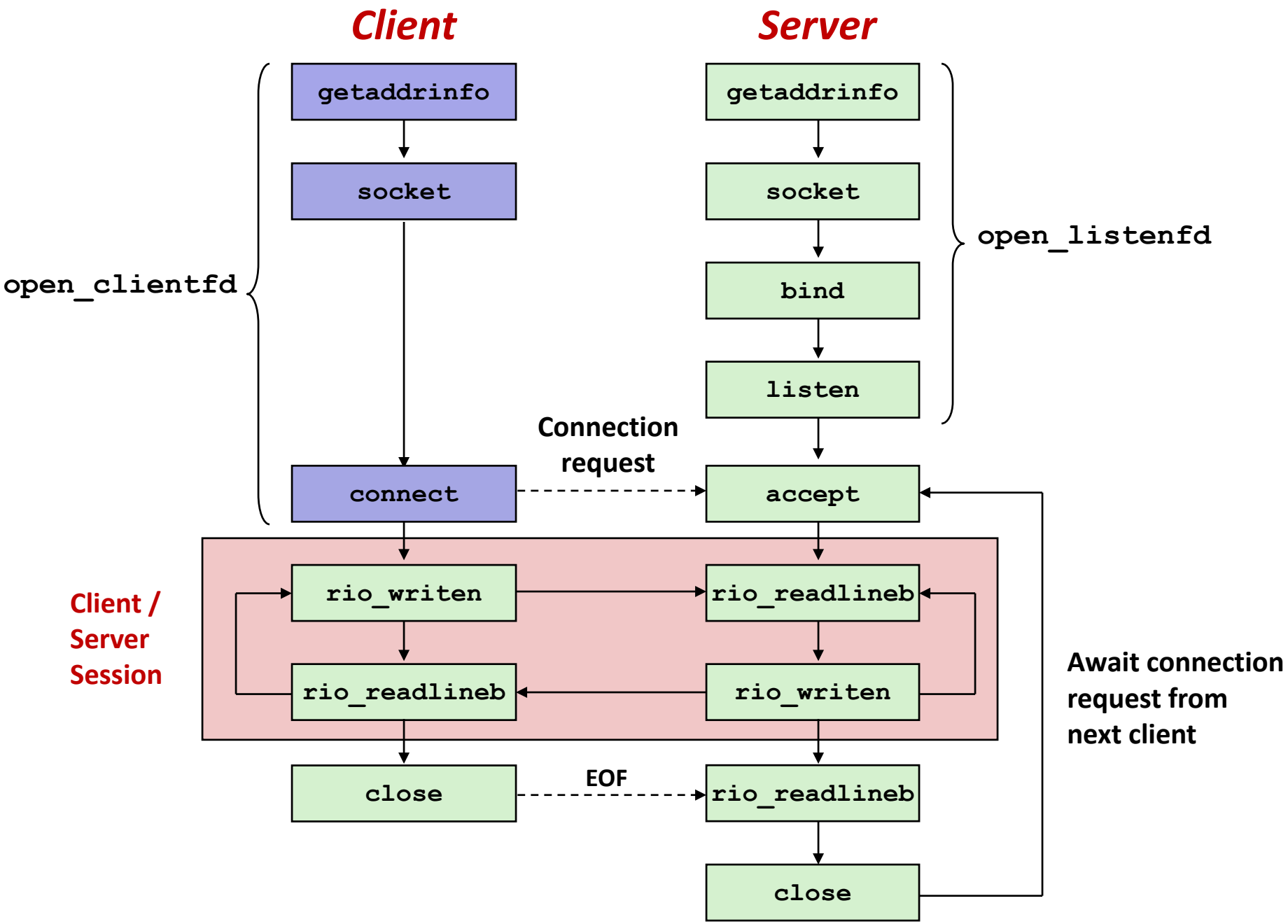
2. Client makes connection request by calling and blocking in `connect`

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


Client
Server
getaddrinfo
getaddrinfo
SA list
SA list
socket
socket
clientfd
listenfd
open_clientfd
open_listenfd
bind
listenfd <-> SA
listen
listening listenfd
Connection request
connect
accept
connected (to SA) clientfd
connected connfd
Client / Server Session
rio_writen
rio_readlineb
rio_readlineb
rio_writen
Await connection request from next client
close
EOF
rio_readlineb
close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rio_writen
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EOF
rio_readlineb
close
Await connection request from next client

Sockets Helper: `open_clientfd`

- Establish a connection with a server

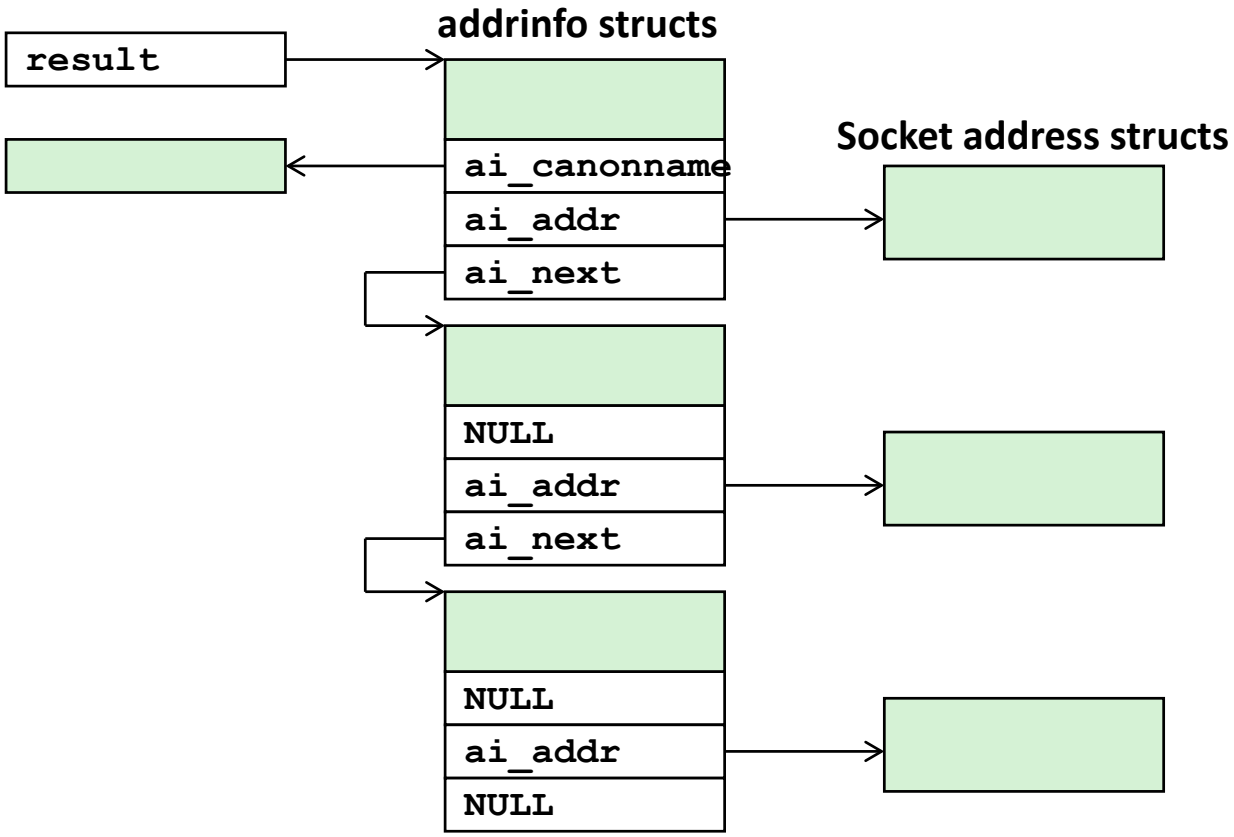
```
int open_clientfd(char *hostname, char *port) {
  int clientfd;
  struct addrinfo hints, *listp, *p;

  /* 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.

getaddrinfo



- Clients: walk this list, trying each socket address in turn, until the calls to `socket` and `connect` succeed.
- Servers: walk the list calling `socket`, `listen`, `bind` for *all* addresses, then use `select` to accept connections on any of them (beyond our scope)

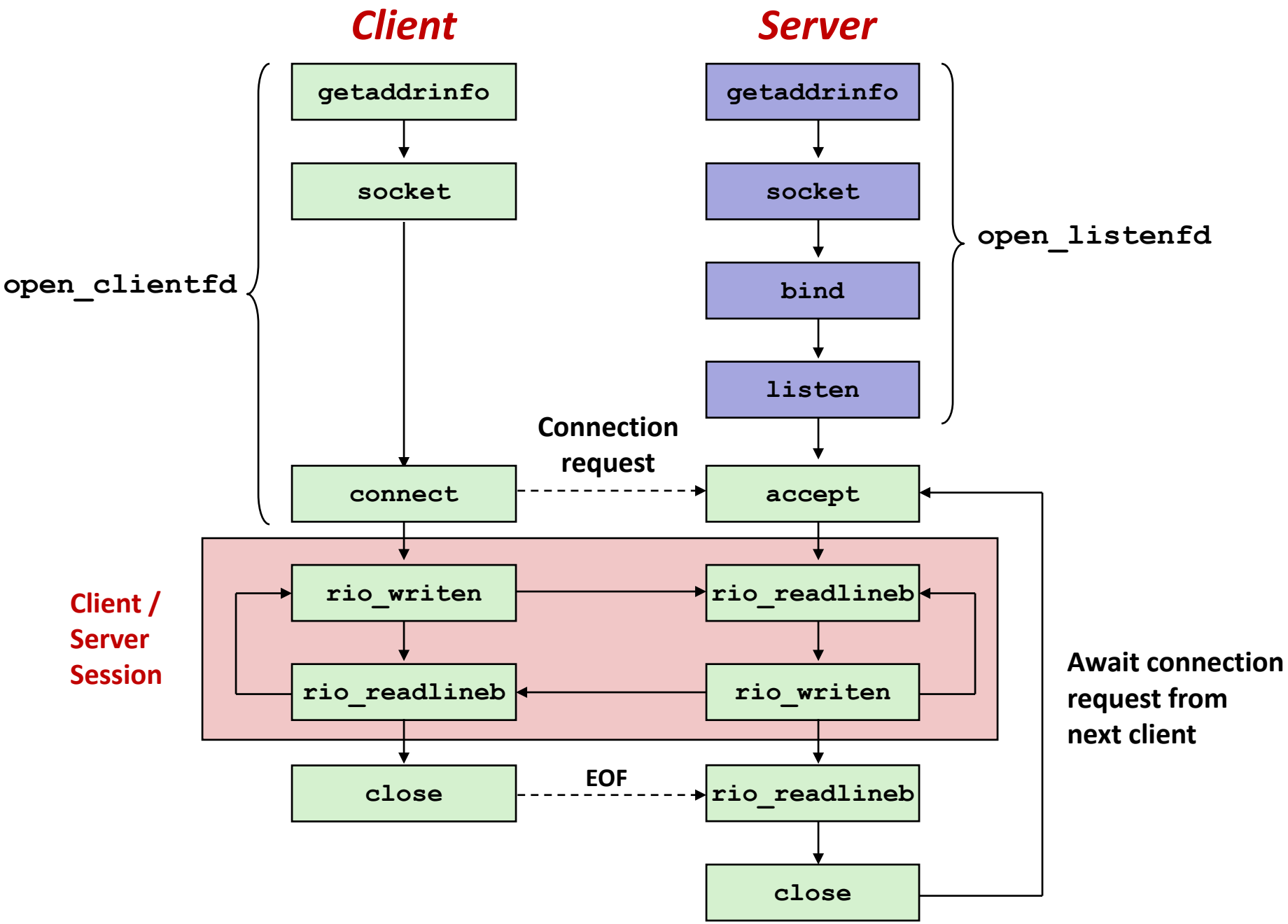
Sockets Helper: `open_clientfd` (cont)

```
    /* 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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rio_writen
close
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rio_readlineb
close
Await connection request from next client

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`

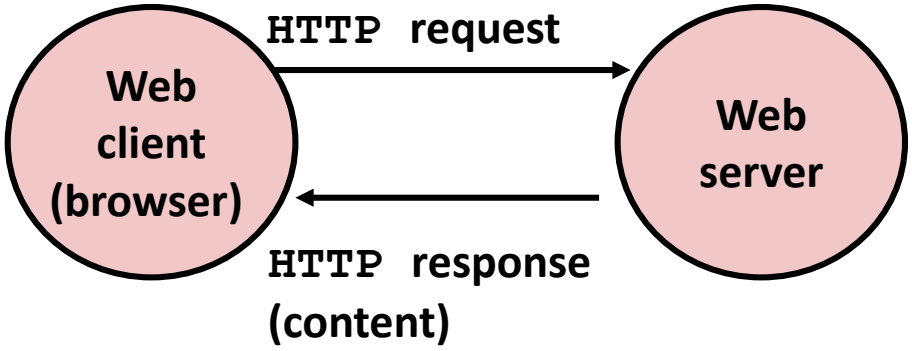
```
whaleshark> ./echoserveri 15213
Connected to (MAKOSHARK.ICS.CS.CMU.EDU, 50280)
server received 11 bytes
server received 8 bytes



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>
```

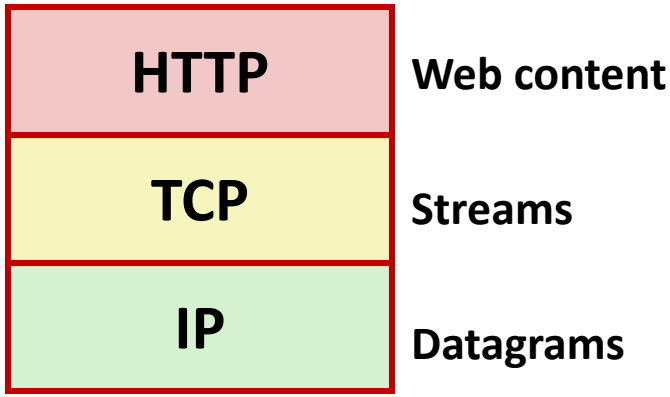
Today

- Questions from yesterday
- Material we didn't get to yesterday
  - Transmitting data using sockets
  - Socket addresses
  - `getaddrinfo`
- Setting up connections
- **Application protocol example: HTTP**

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/2.0 but HTTP/1.1 widely used still**
  - 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 Request Example

```
GET / HTTP/1.1                          Client: request line
Host: www.cmu.edu                       Client: required HTTP/1.1 header
                                        Client: blank line terminates headers
```

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

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 ...
```