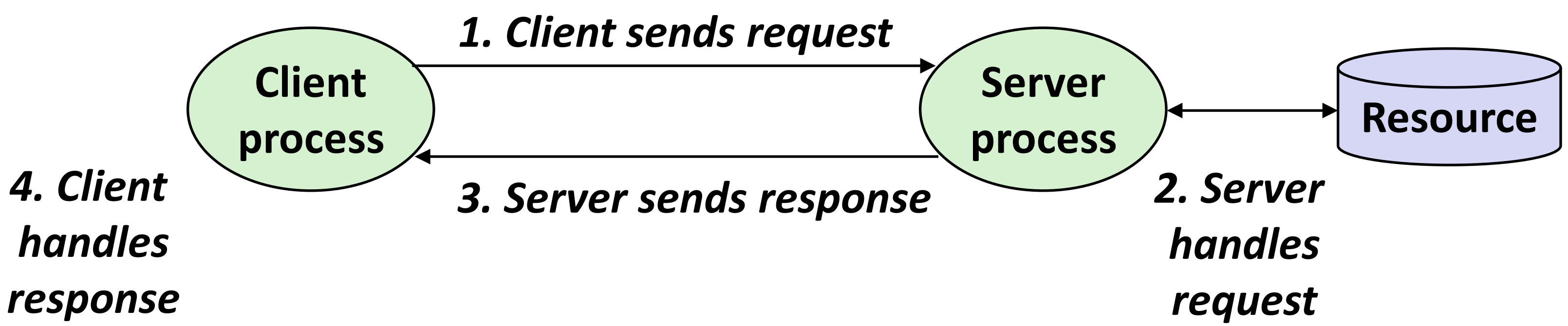
Networking part I: Concepts

CS 485G-006: Systems Programming

Lecture 29: 8 Apr 2016

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)

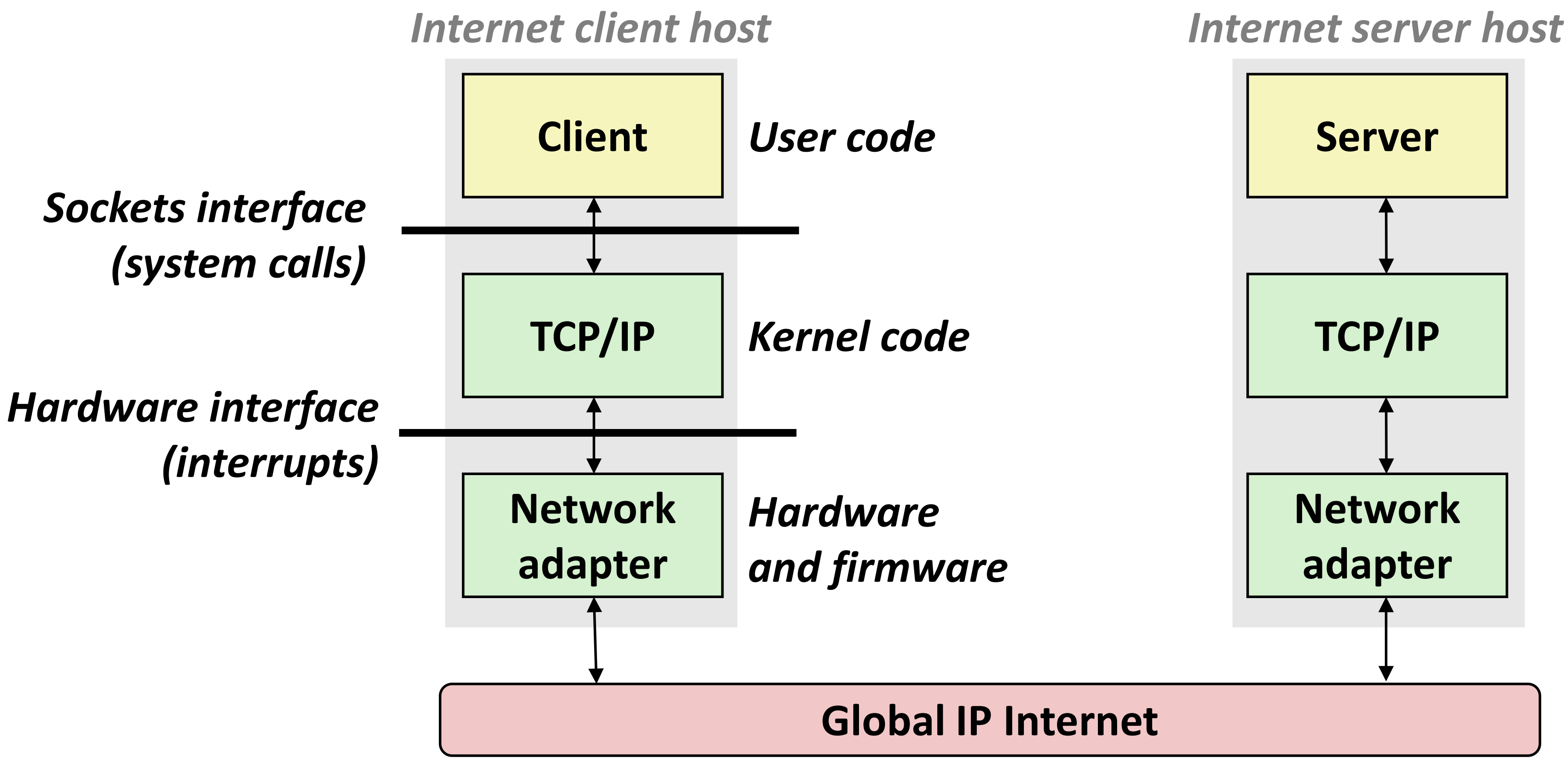
Global IP Internet (upper case)

- **Most famous example of an internet**

- **Based on the TCP/IP protocol family**
  - IP (Internet Protocol) :
    - Provides *basic naming scheme* and unreliable *delivery capability* of packets (datagrams) from *host-to-host*
  - UDP (Unreliable Datagram Protocol)
    - Uses IP to provide *unreliable* datagram delivery from *process-to-process*
  - TCP (Transmission Control Protocol)
    - Uses IP to provide *reliable* byte streams from *process-to-process* over *connections*

- **Accessed via a mix of Unix file I/O and functions from the *sockets interface***

Hardware and Software Organization of an Internet Application



A Programmer's View of the Internet

1. Hosts are mapped to a set of 32-bit *IP addresses*

- 128.2.203.179

2. The set of IP addresses is mapped to a set of identifiers called Internet *domain names*

- 128.2.203.179 is mapped to www.cs.cmu.edu

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

Aside: IPv4 and IPv6

- **The original Internet Protocol, with its 32-bit addresses, is known as *Internet Protocol Version 4* (IPv4)**
- **1996: Internet Engineering Task Force (IETF) introduced *Internet Protocol Version 6* (IPv6) with 128-bit addresses**
  - Intended as the successor to IPv4
- **As of 2015, vast majority of Internet traffic still carried by IPv4**
  - Only 4% of users access Google services using IPv6.
- **We will focus on IPv4, but will show you how to write networking code that is protocol-independent.**

(1) IP Addresses

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

```
/* Internet address structure */
struct in_addr {
    uint32_t  s_addr; /* network byte order (big-endian) */
};
```

  - Opposite byte order from Intel CPUs!
    - Conversion functions: h (host = CPU) and n (network)
      - **htonl**, **ntohl**: 32-bit values
      - **htons**, **ntohs**: 16-bit values

Dotted Decimal Notation

- **By convention, each byte in a 32-bit IP address is represented by its decimal value and separated by a period**
  - IP address: `0x8002C2F2 = 128.2.194.242`

- **Use `getaddrinfo` and `getnameinfo` functions (described later) to convert between IP addresses and dotted decimal format.**

IP Address Structure

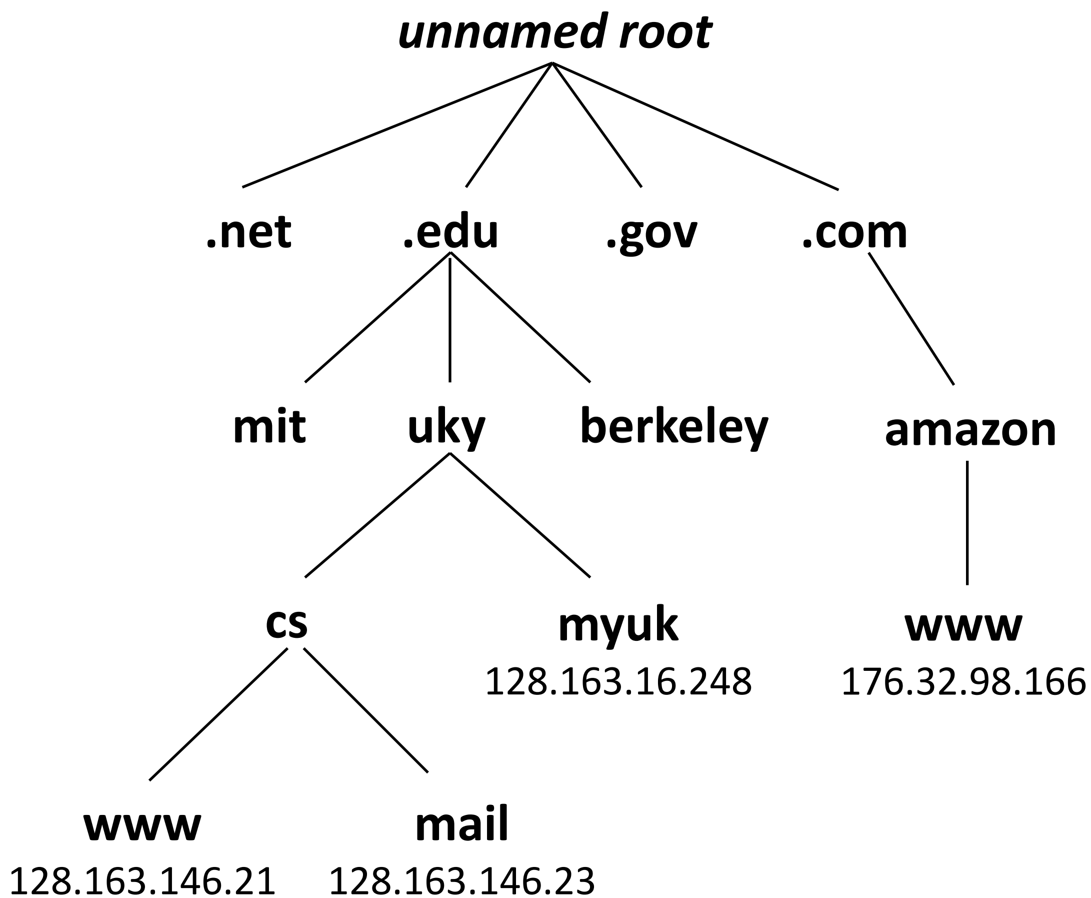
- **IP (V4) Address space divided into classes:**

	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

(2) Internet Domain Names



Top-level domain names (TLDs)

Second-level domain names

Third-level domain names

Domain Name System (DNS)

- **The Internet maintains a mapping between IP addresses and domain names in a huge worldwide distributed database called *DNS***

- **Conceptually, programmers can view the DNS database as a collection of millions of *host entries.***
  - Each host entry defines the mapping between a set of domain names and IP addresses.
  - In a mathematical sense, a host entry is an equivalence class of domain names and IP addresses.

Properties of DNS Mappings

- **Can explore properties of DNS mappings using `nslookup`**
  - Output edited for brevity

- **Each host has a locally defined domain name `localhost` which always maps to the *loopback address* `127.0.0.1`**

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

- **Use `hostname` to determine real domain name of local host:**

```
linux> hostname
whaleshark.ics.cs.cmu.edu
```

Properties of DNS Mappings (cont)

- **Simple case: one-to-one mapping between domain name and IP address:**

```
linux> nslookup whaleshark.ics.cs.cmu.edu
Address: 128.2.210.175
```

- **Multiple domain names mapped to the same IP address:**

```
linux> nslookup cs.mit.edu
Address: 18.62.1.6
linux> nslookup eecs.mit.edu
Address: 18.62.1.6
```

Properties of DNS Mappings (cont)

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

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

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

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

```
linux> nslookup ics.cs.cmu.edu
*** Can't find ics.cs.cmu.edu: No answer
```

(3) Internet Connections

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

- ***A socket* is an endpoint of a connection**
  - *Socket address* is an **`IPaddress:port`** pair

- **A *port* is a 16-bit integer that identifies a process:**
  - ***Ephemeral port*:** Assigned automatically by client kernel when client makes a connection request.
  - ***Well-known port:*** Associated with some *service* provided by a server (e.g., port 80 is associated with Web servers)

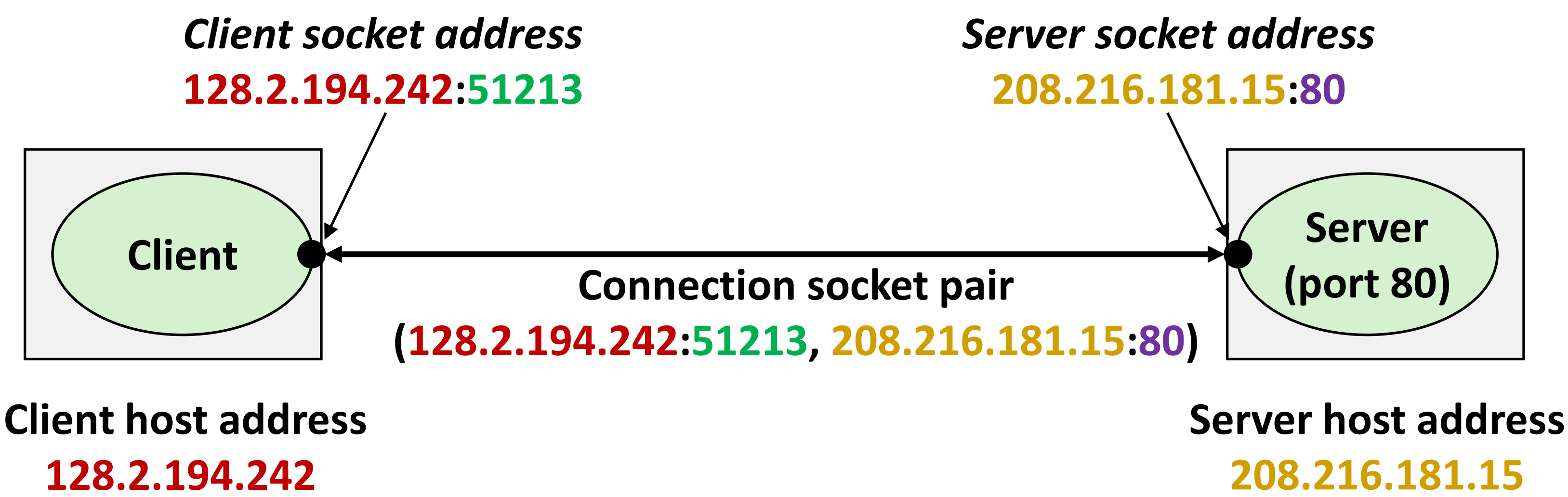
Well-known Ports and Service Names

- **Popular services have permanently assigned *well-known ports* *and* corresponding *well-known service names*:**
  - echo server: 7/echo
  - ssh servers: 22/ssh
  - email server: 25/smtp
  - Web servers: 80/http

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

Anatomy of a Connection

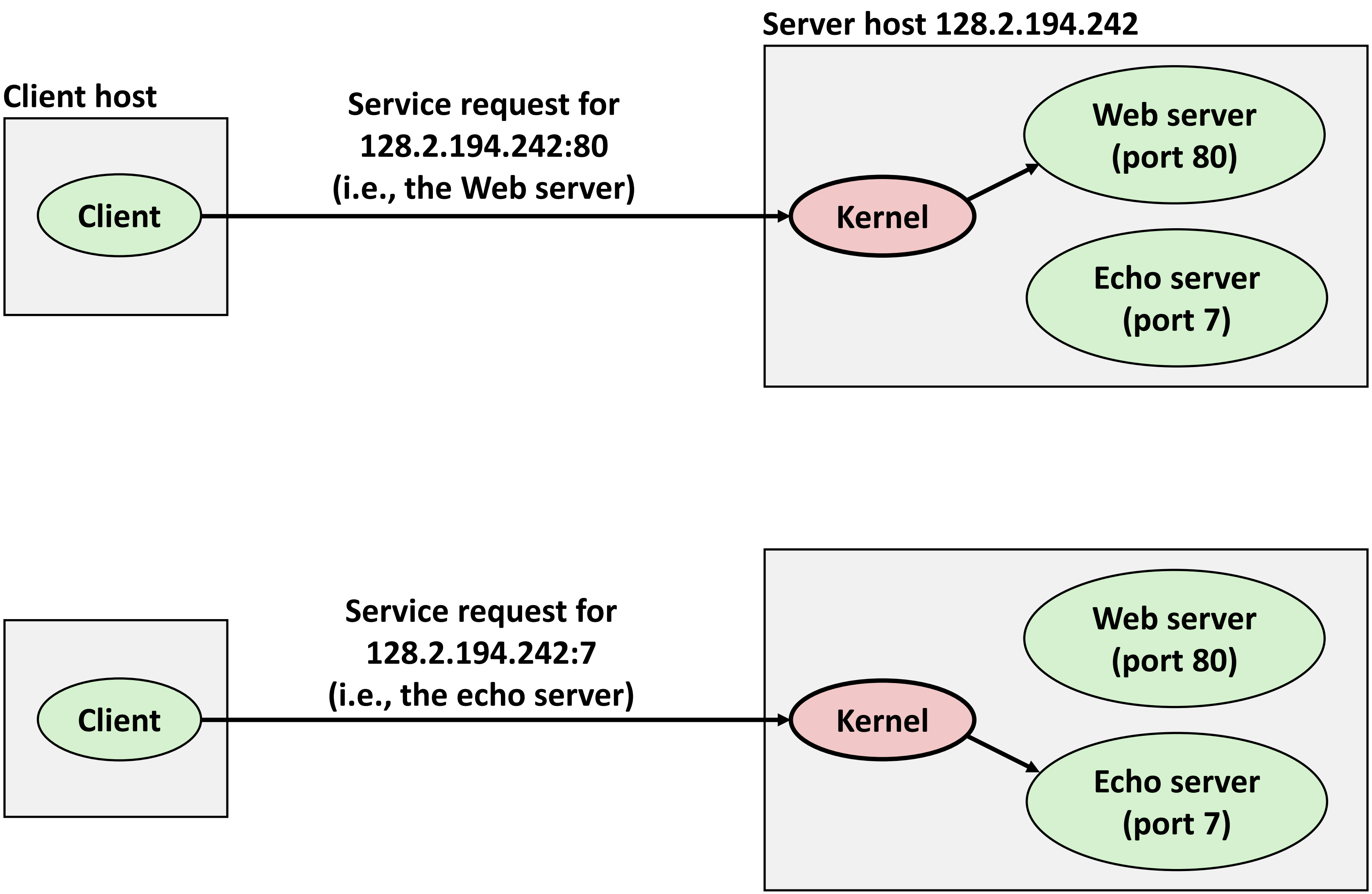
- A connection is uniquely identified by the socket addresses of its endpoints (***socket pair***)
  - `(cliaddr:cliport, servaddr:servport)`



51213 is an ephemeral port allocated by the kernel

80 is a well-known port associated with Web servers

Using Ports to Identify Services



Sockets Interface

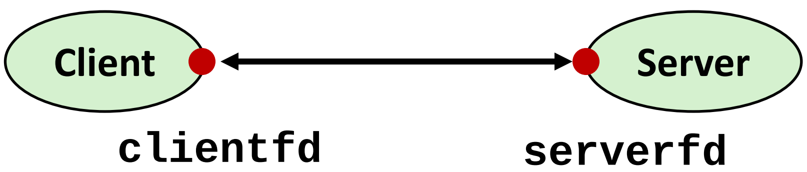
- **Set of system-level functions used in conjunction with Unix I/O to build network applications.**

- **Created in the early 80's as part of the original Berkeley distribution of Unix that contained an early version of the Internet protocols.**

- **Available on all modern systems**
  - Unix variants, Windows, OS X, IOS, Android, ARM

Sockets

- **What is a socket?**
  - To the kernel, a socket is an endpoint of communication
  - To an application, a socket is a file descriptor that lets the application read/write from/to the network
    - ***Remember:*** All Unix I/O devices, including networks, are modeled as files
- **Clients and servers communicate with each other by reading from and writing to socket descriptors**



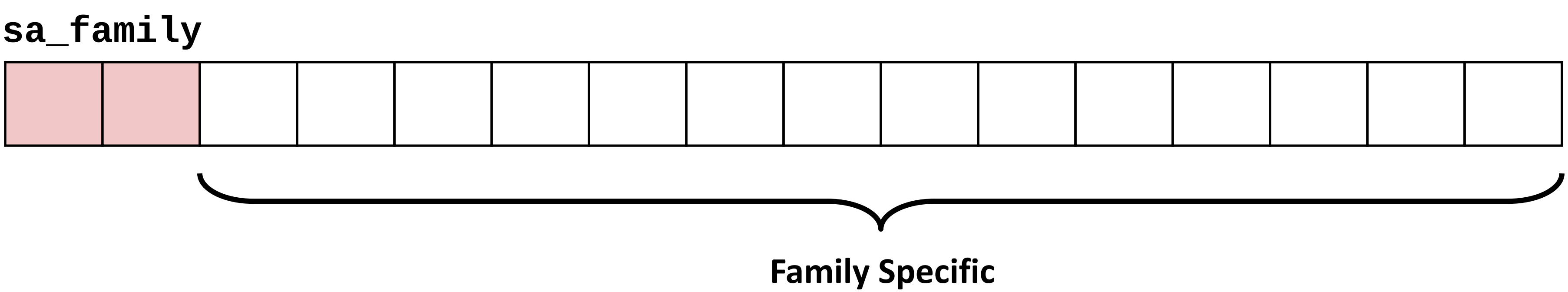
- **The main distinction between regular file I/O and socket I/O is how the application "opens" the socket descriptors**

Socket Address Structures

- **Generic socket address:**
  - For address arguments to **`connect`**, **`bind`**, and **`accept`**
  - Necessary only because C did not have generic (**`void *`**) pointers when the sockets interface was designed
  - For casting convenience, we adopt the Stevens convention:

    `typedef struct sockaddr SA;`

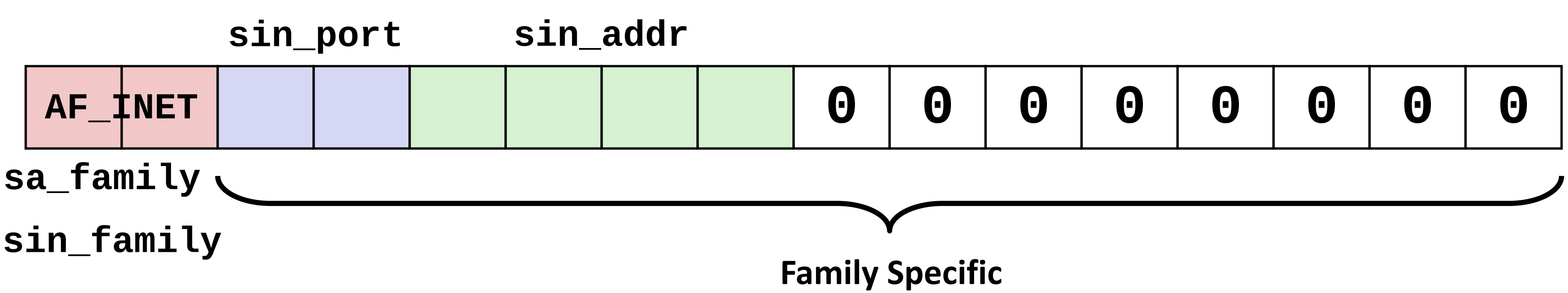
```
struct sockaddr {
  uint16_t  sa_family;    /* Protocol family */
  char      sa_data[14];  /* Address data.   */
};
```



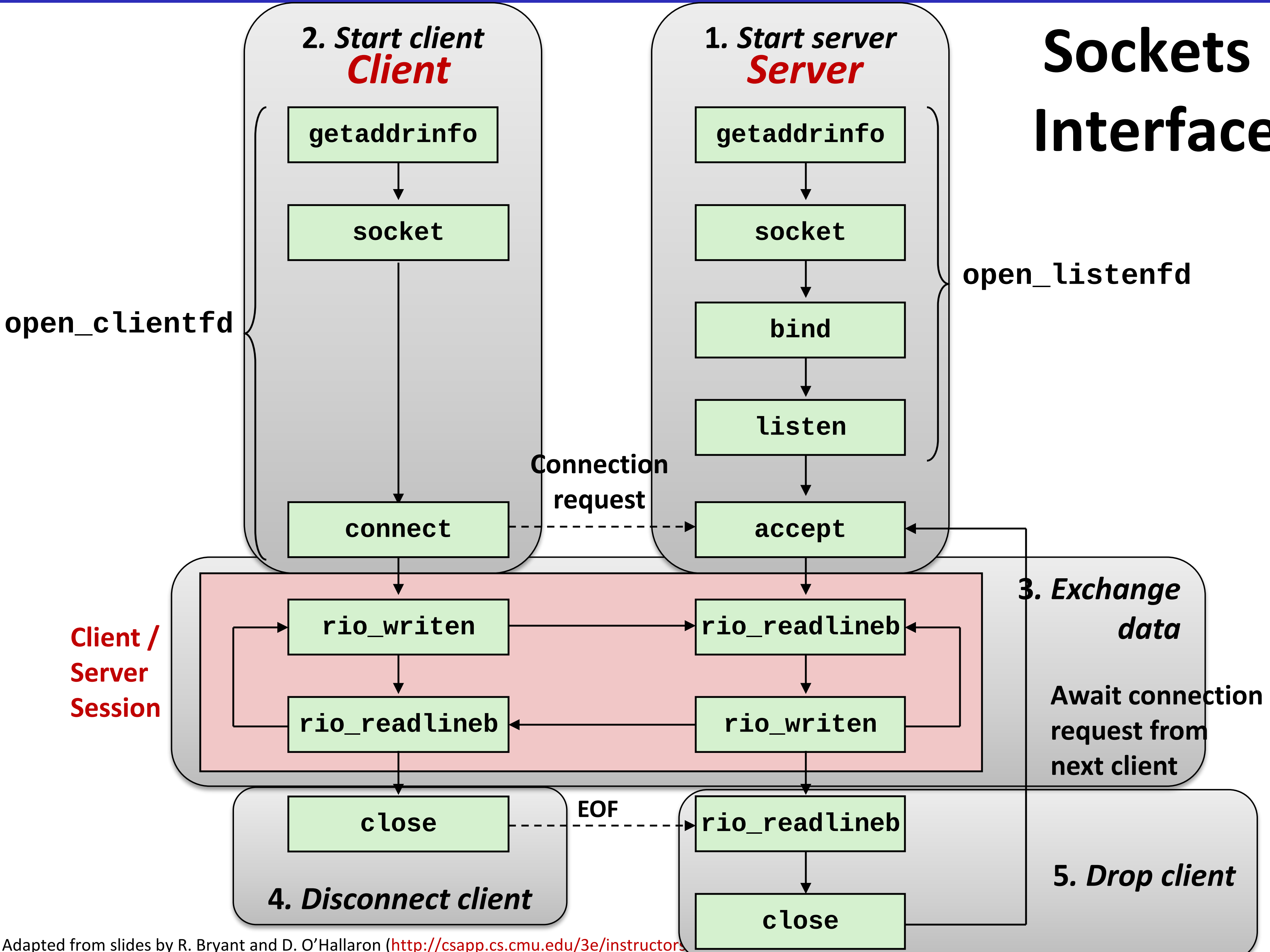
Socket Address Structures

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

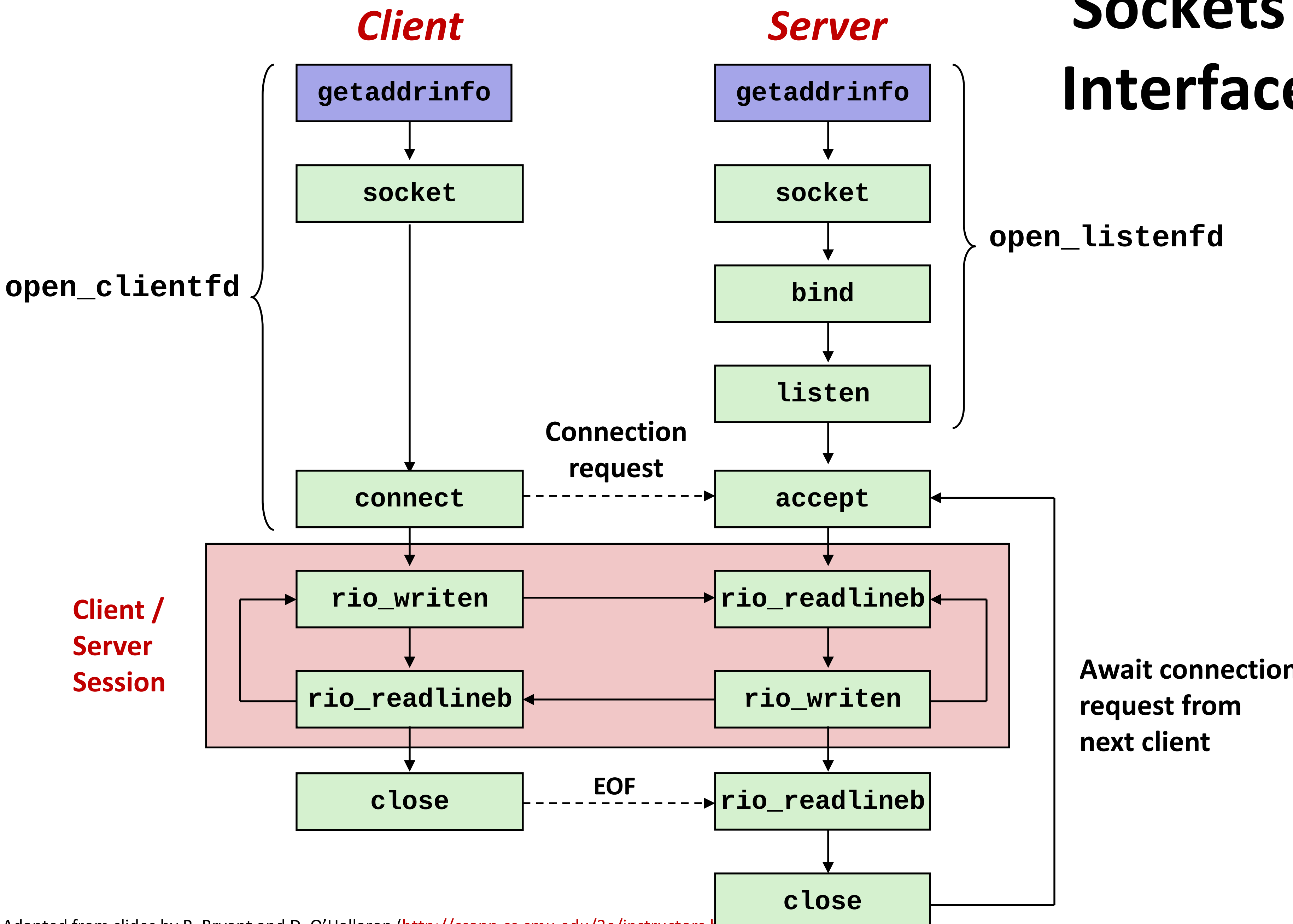
```
struct sockaddr_in  {
  uint16_t        sin_family;  /* Protocol family (always AF_INET) */
  uint16_t        sin_port;    /* Port num in network byte order */
  struct in_addr  sin_addr;    /* IP addr in network byte order */
  unsigned char   sin_zero[8]; /* Pad to sizeof(struct sockaddr) */
};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



Sockets Interface



Sockets Interface



Host and Service Conversion: `getaddrinfo`

- **`getaddrinfo` is the modern way to convert string representations of hostnames, host addresses, ports, and service names to socket address structures.**
  - Replaces obsolete `gethostbyname` and `getservbyname` funcs.

- **Advantages:**
  - Reentrant (can be safely used by threaded programs).
  - Allows us to write portable protocol-independent code
    - Works with both IPv4 and IPv6

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

Host and Service Conversion: `getaddrinfo`

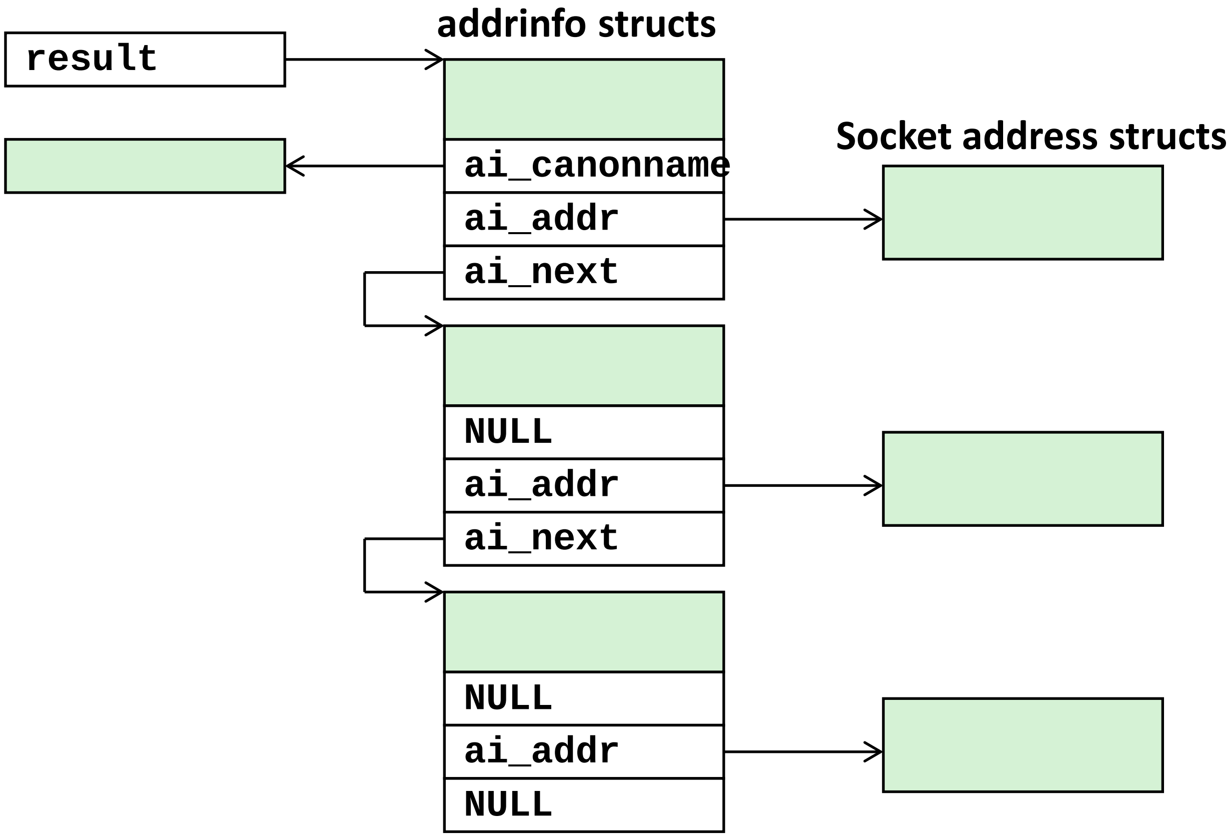
```
int getaddrinfo(const char *host,            /* Hostname or address */
                const char *service,         /* Port or service name 
*/
                const struct addrinfo *hints,/* Input parameters */
                struct addrinfo **result);   /* Output linked list */

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

```
#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
```